DECEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

The Paramagnetic Susceptibility of Copper-Nickel and Zinc-Nickel Alloys

MARY A. WHEELER
*Yale University, New Haven, Connecticut**

(Received October 11, 1939)

Alloys of nickel were prepared with 0 to 60 percent copper or 0 to 30 percent zinc. Their susceptibilities above their Curie temperatures were measured as a function of the temperatures using a Weiss-Foëx magnetic balance at a field of 11,000. Plots of $1/\chi$ against T showed that the Curie-Weiss law holds only in restricted ranges of temperature, the curve becoming concave towards the T axis at high temperatures, especially for the alloys of low nickel content. The susceptibility at a given temperature decreases less rapidly than linearly with percent copper or zinc added. These results are discussed from the points of view of the Heisenberg and the Bloch models.

THE theory of the strong paramagnetism of the ferromagnetic metals and alloys above their Curie points is still in an unsatisfactory state. In general these substances have a region some distance above their Curie points in which the reciprocal of the susceptibility, $1/\chi$, is a linear function of $(T-\theta_p)$, where θ_p is the paramagnetic Curie temperature, while in the region immediately above the Curie point there is a strong curvature. The molecular field theory of Pierre Weiss explains this linearity on a phenomenological basis by the assumption of a "molecular field" in addition to the externally applied field. The attempts to place the molecular field on a theoretical basis were unsatisfactory until Heisenberg showed that the exchange force between the electronic spins in an incomplete inner shell, such as the 3*d* electrons of nickel, would introduce just such a term. Numerous calculations based on the Heisenberg model have proved the difficulty of determining the actual value of this term. Opechowski[1] has carried out a series development, which incorporates preceding results of Heisenberg, and which leads to contradictory results with successive approximations, showing that the convergence is too slow for this method to be reliable. P. R. Weiss and J. H. Van Vleck[2] applied the Bethe-Peierls method devised for order-disorder transitions. From their calculations a nearly linear relation is found to exist between $1/\chi$ and T over some ranges of temperature but this linearity is accidental and of limited range.

All calculations based on the Heisenberg model are necessarily approximations. This is due to the nature of the model itself which assumes that the electrons responsible for the ferromagnetism are permanently attached to their atoms, thus neglecting any transfer of electrons from atom to atom. Stoner,[3] in the alternative method of attack, has used the Bloch modal and treats the 3*d* as well as the 4*s* electrons in nickel, for example, as collective electrons, belonging to the metal as a whole. Similarly Mott[4] has explained the ferromagnetic saturation moment of nickel (0.6 Bohr magneton) by assuming that the 4*s* energy band is so broadened that it overlaps the 3*d* band, and in consequence the outer ten electrons in nickel are divided between the 3*d* and the 4*s* bands in such a way that on the average there is 0.6 electron per atom in the 4*s* band and 0.6 electron per atom missing from the 3*d* band. The ferromagnetic moment below the Curie point and the paramagnetic moment above it are then due to the holes in the 3*d* band; the 4*s* electrons cannot contribute magnetic moment because of the great width of the band. Mott adds to this a neat explanation of the change of Curie point and of atomic moment of nickel when alloyed with another metal, such as copper or zinc, which has its 3*d* shell full and one or two 4*s* electrons besides. The 3*d* band is much narrower than the 4*s* band and thus the density of

---

* This work was done during a leave of absence from Vassar College as Faculty Fellow, 1937–8.

[1] W. Opechowski, Physica **4**, 181 (1937).

[2] P. R. Weiss and J. H. Van Vleck, Phys. Rev. **55**, 673 (1939).

[3] E. C. Stoner, *Magnetism and Matter* (Methuen and Company, London, 1934), p. 431.

[4] N. F. Mott and H. Jones, *The Theory of the Properties of Metal and Alloys* (Oxford University Press, 1936), p. 192.

energy states is much greater. It follows that, on the formation of alloys of nickel, the 4*s* electrons supplied by copper or zinc will tend to fall into the holes in the 3*d* band of the alloy until the 3*d* band is full. This will occur at 60 percent copper or 30 percent zinc. This theory is supported by the ferromagnetic properties of these alloys. Sadron[5] has shown, if some extrapolation is allowed, that the saturation moment per nickel atom and likewise the Curie temperature decrease in proportion to the copper or zinc added, reaching zero at 60 percent copper or 30 percent zinc. Later we shall see that this support is not so complete as is usually supposed.

The paramagnetic susceptibility above the Curie point also must depend upon the distribution of electrons between 3*d* and 4*s* states. Stoner[6] has carried out this analysis. He finds the observed curvature in the $1/\chi - T$ curve directly above the Curie point consistent with this theory. A linear relation holds at high temperatures because the energy changes fixed by the band structure are relatively less important. Deviations from the Curie-Weiss law in this region may still be explained by a change in the band form or in the number of electrons in the band.

Presumably the actual explanation is somewhere between these two extreme hypotheses and it is accordingly more difficult to formulate. It may be argued that the Heisenberg model is better than the Bloch model in nickel. The reason is that the 3*d* electrons, which alone are responsible for ferromagnetism in nickel, are rather firmly attached to their atoms. The fact that nickel has an atomic saturation moment of 0.6 Bohr magneton may mean that 60 percent of the nickel atoms are momentarily in the configuration $3d^9 4s$ and 40 percent in $3d^{10}$. In the alloy there may be a redistribution of the nickel atoms between these configurations. Analyses so far completed fail to include properly fluctuations of atoms between possible configurations. Since the calculations based on the Heisenberg model necessarily neglect the energy associated with the transfer of electrons, results derived from this model may be expected to be in error. The calculated susceptibility will probably be too high.

Another possible error in the results calculated from either model may be attributed to the neglect of the influence of the orbital motion of electrons upon the magnetic susceptibility. In all known cases except that of pyrrhotite the orbital momentum must be nearly quenched at room temperature because the gyromagnetic ratio is almost 2, which would be the value for the electron spin alone. The mechanism for the quenching of this orbital momentum is unexplained on the Heisenberg model. It may be possible that at higher temperatures the orbital momentum might make a contribution to the susceptibility. Since the gyromagnetic ratio is nearly the same for the various metals and their alloys the crystalline field is probably unimportant. The Bloch model explains the quenching as a result of the wandering of electrons from atom to atom. It may also be noted that an antiferromagnetic coupling between the orbital angular momenta may be present and cause such a quenching;[7] this is not considered in any of the theories.[8]

In view of the theoretical uncertainties reviewed above it seemed worth while to carry out precise measurements on the susceptibilities of nickel-copper and nickel-zinc alloys above their Curie points. Copper forms a complete series of solid solutions with nickel and zinc is also very soluble in nickel, the solubility limit lying at 30 percent. In both cases there is only a small change in the lattice constant.[9] Copper and zinc immediately succeed nickel in the periodic table. Thus an atom of nickel in either series of alloys is in a situation very similar to that in the pure metal except that each atom of copper has added one extra electron to the alloy and each atom of zinc has added two. With increasing dilution of nickel and greater average separation between nickel atoms both the ferromagnetic coupling between the 3*d* electronic spins and the antiferromagnetic coupling of their orbital angular momenta should decrease, and temperature changes dependent upon these factors might be especially apparent.

The paramagnetic susceptibility of copper-

---

[5] C. Sadron, Ann. de physique **17**, 371 (1932).

[6] E. C. Stoner, Proc. Roy. Soc. **A165**, 372 (1938).

[7] A. Sommerfeld and H. A. Bethe, *Handbuch der Physik*, second edition, Vol. 24, No. 2, p. 613.

[8] An excellent review of this subject by J. H. Van Vleck is soon to appear in Ann. de l'Institut Henri Poincaré.

[9] S. Holgersson, Ann. d. Physik **79**, 35 (1926); J. Schramm, Zeits. f. Metallkunde **30**, 122 (1938).

nickel alloys above their Curie points has already been investigated. The most consistent results are those of Alder[10] and Gustafsson.[11] Alder measured the values of the susceptibility from −190°C to 750°C and found at all temperatures a decrease in susceptibility as the percent of copper increased, with certain unexplained irregularities. Gustafsson repeated this work but did not find the irregularities previously noted. His measurements extended from room temperature to 450°C. In the present investigation this range has been extended to 800°C, and results compared with similar measurements on zinc-nickel alloys. Since this work was undertaken, the magnetic properties of zinc-nickel have been reported by Schramm.[12] Quantitative comparison is difficult because of the form of the published data.

Preparation of Alloys

The alloys were prepared from the purest metals obtainable. The base material was Baker's C. P. nickel, purified further by the rotating cathode method of Fink. This material was prepared by Lawrence Ott in 1931 and has been used in other investigations in this laboratory. This was alloyed with Hilger electrolytic copper, 99.995 percent pure, containing oxygen as the chief impurity. The zinc used was prepared for spectrographic analysis by the New Jersey Zinc Co. and was of 99.999 percent purity. The copper alloys were melted in magnesia crucibles under hydrogen at atmospheric pressure, then pounded to hasten homogenizing, and annealed at a temperature of 900°C for a week. It was very important that homogenizing should be complete since even slight segregations of nickel atoms would cause a large error. As the zinc alloys could not be made in an open crucible, owing to the high volatility of zinc, the zinc and nickel were sealed under a pressure of 10^{-5} mm or less in a small tube of fused silica and annealed at a temperature of 1000°C for a week so that the zinc completely diffused through the nickel. It was impossible to melt these alloys under these conditions due to the low softening point of the container. Spectrographic test for silicon gave negative results.

The homogeneity of the 15 percent copper alloy was tested in two ways, magnetically and microscopically. Specimens of the same melt were polished, etched and examined microscopically by Dr. R. M. Brick of the Department of Metallurgy, after two, five, and seven days homogenizing. No inhomogeneity could be detected even in the two-day sample. The abruptness of the transition at the Curie temperature has been shown by Marian[13] to be a proof of homogeneity. The transition becomes more abrupt as length of time for homogenizing is increased until a limit is reached when most of the change occurs within from 5 to 20° for copper alloys between 0 and 12 percent, 30 to 60° for 12 to 35 percent copper, and over 60° for alloys with more than 35 percent copper. For this 15 percent alloy the corresponding range in the specimen annealed for two days was 35°, for the one annealed for seven days was 15°. Therefore the magnetic method of test was more sensitive than the microscopic and was used subsequently for all alloys with a Curie point above room temperature. In each case it was found that the transition took place within the temperature limits just quoted from Marian.

The mean composition of these alloys reported was determined by chemical analysis. In different parts of the copper-nickel melt the composition as cast differed by as much as 1 percent for the 15 percent alloy and 2 percent for the 60 percent alloy. The zinc-nickel was of much more uniform composition, the greatest deviation being 0.5 percent for the 9 percent alloy.

The 13 percent copper sample of the copper-nickel series was supplied by Dr. R. M. Bozorth of the Bell Laboratories. This was synthesized from Mond nickel (0.03 percent Fe) and Hilger spectroscopically pure copper.

Magnetic Measurements

A Weiss-Foëx translation balance with a large Weiss magnet was used for the magnetic measurements. The furnace used was similar to one described by Foëx and Forrer[14] and the temperatures were measured by a Chromel-alumel thermocouple calibrated by the melting points of Bi and Sn as indicated by the change of sus-

---

[10] M. Alder, Thèse, Zurich (1916).

[11] G. Gustafsson, Ann. d. Physik **28**, 121 (1937).

[12] J. Schramm, Zeits. f. Metallkunde **30**, 327 (1938).

[13] V. Marian, J. de phys. et rad. [7] **8**, 313 (1937).

[14] G. Foëx and R. Forrer, J. de phys. et rad. [6] **7**, 180 (1926).

TABLE I. *Mass susceptibilities of* CuNi *alloys. The results on two different specimens are given for each alloy.*

T(°K)	$\chi\times10^{6}$	$1/\chi\times10^{-4}$
13.0 percent Cu by weight		
599	51.85	1.929
635	36.50	2.740
695	25.01	3.998
743	19.98	5.005
816	15.06	6.640
879	12.63	7.918
899	12.04	8.306
973	10.28	9.728
995	9.75	10.26
1071	8.33	12.00
518	225.15	.4441
563	80.64	1.240
582	61.99	1.613
633	36.26	2.759
680	26.77	3.736
712	22.51	4.442
789	16.30	6.135
833	14.30	6.993
952	10.64	9.398
1084	8.45	11.84
15.0 percent Cu by weight		
558	72.63	1.377
575	57.92	1.727
633	32.81	3.048
669	25.98	3.849
721	20.30	4.926
808	14.76	6.775
854	12.87	7.770
913	11.24	8.897
983	9.83	10.17
1054	8.77	11.40
593	50.65	1.974
600	45.94	2.177
640	33.39	2.995
691	24.57	4.070
741	19.20	5.208
789	15.96	6.266
890	12.08	8.278
939	10.85	9.217
22.7 percent Cu by weight		
471	81.65	1.225
484	69.09	1.447
487	63.22	1.582
497	55.40	1.805
511	48.41	2.066
533	37.96	2.634
547	32.75	3.053
554	32.39	3.087
582	26.01	3.845
596	23.37	4.279
602	23.48	4.259
629	20.53	4.871
645	18.29	5.467
701	14.93	6.698
754	12.79	7.819
518	42.66	2.344
550	31.89	3.136
602	22.62	4.421
626	19.53	5.120
654	17.69	5.653
660	16.22	6.165
689	15.02	6.658
722	13.54	7.386
729	13.36	7.485
766	11.84	8.446
792	10.98	9.107
855	9.47	10.56
882	8.96	11.16
933	8.24	12.14
971	7.71	12.97
28.7 percent Cu by weight		
475	31.58	3.167
500	25.69	3.893
561	17.33	5.770
573	16.46	6.075
612	13.73	7.283
642	12.37	8.084
693	10.77	9.285
753	9.17	10.91
809	8.10	12.34
876	7.07	14.15
957	6.26	15.98
429	52.46	1.906
454	39.89	2.507
483	29.14	3.432
534	20.34	4.916
580	15.94	6.274
625	13.35	7.491
668	11.36	8.803
724	9.78	10.22
765	8.87	11.27
37.0 percent Cu by weight		
331	53.30	1.876
380	28.84	3.467
397	25.24	3.962
442	17.97	5.565
489	13.53	7.391
539	10.97	9.116
573	9.82	10.18
609	8.81	11.36
657	7.63	13.10
687	7.13	14.02
751	6.31	15.85
412	21.31	4.693
483	13.80	7.246
550	10.37	9.643
607	8.66	11.55
641	7.97	12.54
688	7.18	13.93
721	6.73	14.85
775	6.08	16.44
840	5.52	18.11
876	5.26	19.02
941	4.87	20.54
970	4.73	21.14
49.6 percent Cu by weight		
293	11.78	8.489
346	8.45	11.84
404	6.83	14.65
439	6.26	15.96
446	6.16	16.24
496	5.35	18.70
565	4.71	21.24
584	4.55	21.97
654	4.12	24.25
690	4.03	24.83
735	3.79	26.47
749	3.71	26.92
806	3.53	28.32
852	3.37	29.67
911	3.22	31.02
293	11.37	8.79
345	8.10	12.34
396	6.93	14.43
447	5.95	16.79
501	5.18	19.32
563	4.51	22.17
606	4.29	23.33
650	3.97	25.21
703	3.78	26.46
747	3.57	27.98
827	3.31	30.21
897	3.15	31.74
948	3.05	32.79
60.9 percent Cu by weight		
295	3.30	30.25
341	3.01	33.17
382	2.78	35.94
439	2.58	38.76
480	2.52	39.64
530	2.43	41.18
580	2.35	42.45
627	2.31	43.26
635	2.30	43.52
728	2.20	45.39
810	2.12	47.08
294	3.27	30.61
345	2.95	33.92
399	2.68	37.30
447	2.58	38.68
504	2.43	41.07
557	2.35	42.54
612	2.27	44.05
655	2.23	44.82
709	2.18	45.87
757	2.13	47.04
819	2.07	48.40
857	2.04	48.97
900	2.01	49.85
976	1.97	50.84

TABLE II. *Mass susceptibilities of* ZnNi *alloys. The results on two different specimens are given for each alloy.*

T(°K)	$\chi\times10^{6}$	$1/\chi\times10^{-4}$	T(°K)	$\chi\times10^{6}$	$1/\chi\times10^{-4}$	T(°K)	$\chi\times10^{6}$	$1/\chi\times10^{-4}$
	5.1 percent Zn by weight			*17.0 percent Zn by weight*			*26.2 percent Zn by weight*	
677	43.69	2.289	445	26.38	3.791	293	9.09	11.00
709	33.47	2.988	487	19.80	5.051	346	7.54	13.26
722	31.42	3.183	554	14.51	6.892	398	6.53	15.31
779	22.70	4.405	603	12.40	8.065	443	5.96	16.79
816	19.45	5.141	646	10.83	9.234	505	5.28	18.93
863	16.27	6.146	692	9.75	10.25	563	4.85	20.62
902	14.65	6.826	743	8.69	11.50	594	4.65	21.52
926	13.66	7.321	806	7.64	13.09	669	4.26	23.45
993	11.70	8.547	849	7.16	13.97	723	4.06	24.62
			905	6.74	14.83	848	3.72	26.87
			935	6.56	15.24	904	3.59	27.84
						959	3.51	28.51
656	51.22	1.952	406	37.65	2.656	293	9.14	10.93
690	38.63	2.589	423	32.51	3.076	347	7.49	13.35
716	31.59	3.166	452	25.55	3.914	394	6.67	14.99
769	23.41	4.272	497	18.74	5.336	468	5.75	17.39
790	21.53	4.645	558	14.37	6.959	518	5.23	19.11
833	18.21	5.491	572	13.52	7.396	593	4.66	21.47
864	16.37	6.109	654	10.47	9.551	687	4.15	24.09
890	15.06	6.640	688	9.55	10.47	739	3.97	25.17
914	14.09	7.097	693	9.37	10.67	817	3.75	26.66
951	12.80	7.812				843	3.68	27.18
						911	3.54	28.22
						974	3.44	29.10
	9.1 percent Zn by weight			*21.2 percent Zn by weight*			*29.7 percent Zn by weight*	
590	46.68	2.145	295	32.60	3.067	293	5.22	19.14
626	32.52	3.075	363	18.88	5.297	327	5.02	19.92
658	27.65	3.617	419	13.95	7.168	371	4.61	21.69
687	22.29	4.486	479	11.00	9.091	396	4.36	22.93
744	18.11	5.522	545	8.79	11.38	441	4.12	24.24
749	17.17	5.824	600	7.80	12.82	502	3.84	26.01
818	14.06	7.112	642	7.11	14.07	582	3.55	28.14
847	12.74	7.849	688	6.59	15.18	645	3.40	29.38
855	12.54	7.974	742	6.08	16.45	698	3.31	30.24
902	11.27	8.873	782	5.80	17.25			
954	10.13	9.872	823	5.55	18.00			
957	10.07	9.930	885	5.17	19.33			
991	9.51	10.52	962	4.90	20.41			
1001	9.38	10.66						
518	132.45	0.7553	294	33.13	3.018	293	5.14	19.44
536	92.50	1.081	309	27.06	3.695	345	4.66	21.45
558	65.27	1.532	312	26.48	3.776	449	3.97	25.18
570	58.11	1.721	338	21.64	4.621	510	3.69	27.06
604	39.49	2.532	366	18.04	5.543	554	3.54	28.26
625	33.11	3.020	383	16.28	6.143	610	3.42	29.21
650	28.27	3.537	476	11.06	9.042	664	3.25	30.77
679	23.88	4.188	514	9.80	10.21	745	3.11	32.18
702	21.23	4.710	517	9.60	10.42	835	2.99	33.44
729	19.08	5.241	592	8.04	12.44	900	2.91	34.38
751	17.31	5.777	683	6.71	14.89	957	2.86	34.94
784	15.61	6.406	689	6.72	14.88			
			765	6.05	16.54			
			832	5.62	17.80			
			883	5.32	18.81			
			947	5.03	19.88			

ceptibility. As only relative susceptibilities were obtained by this method, absolute values were found by comparison with a standard of pure gold of known mass susceptibility $(0.145\pm0.001)\times10^{-6}$.

For these measurements the specimens were sealed into silica tubes under a pressure of 10^{-5} mm to prevent change of composition due to diffusion and oxidation. After a measurement at a high temperature a repetition of one at a low temperature was made as a test for any permanent change which might have occurred in

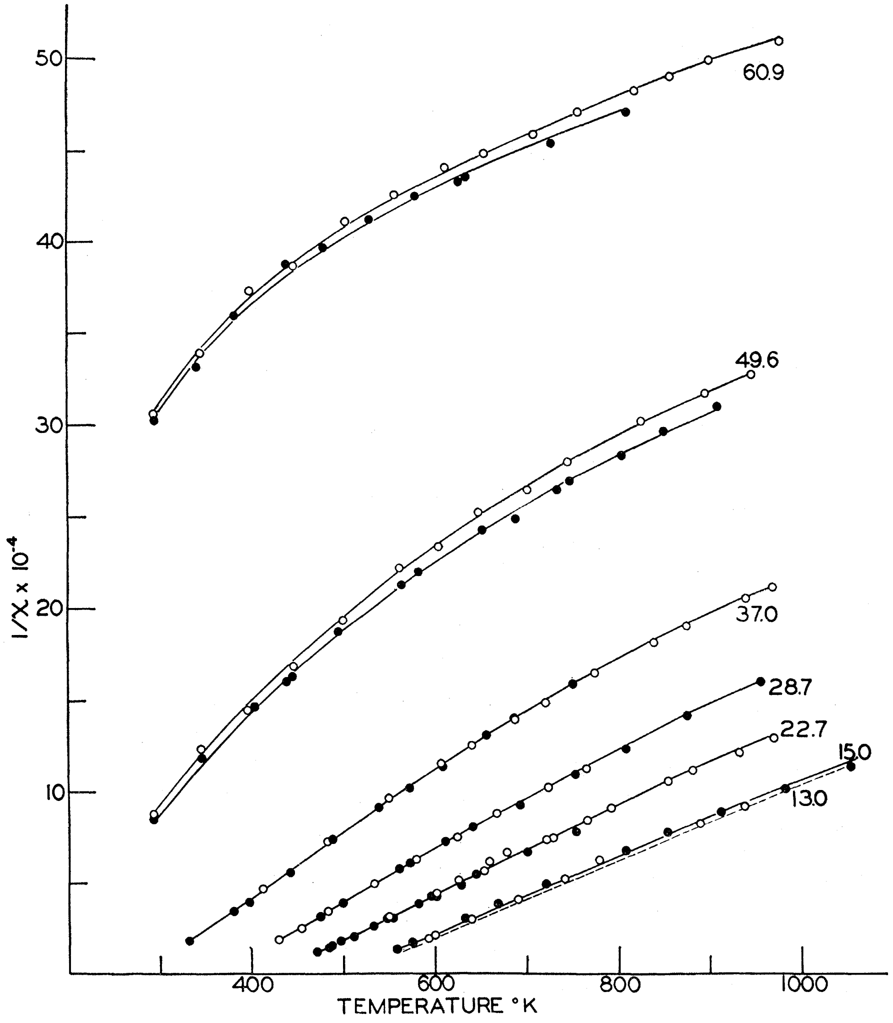

FIG. 1. Reciprocals of mass susceptibilities of CuNi alloys plotted against the temperatures for various percents of copper.

the specimen. When a run had been completed the container was cracked open, the specimen removed, and the susceptibility of the silica measured separately.

To prove the absence of ferromagnetic impurity (e.g., undissolved nickel) the susceptibility was measured at several values of the magnetic field between 3000 and 15,000, at both room and higher temperatures, and in no case was there a deviation from proportionality between susceptibility and field. Subsequently measurements of susceptibility *versus* temperature were taken at a fixed field of 11,350.

DISCUSSION OF RESULTS

Tables I and II give the data, T and χ, and the calculated values of $1/\chi$ for the copper and zinc alloys, respectively. These results are presented graphically in Figs. 1–4, a separate curve being drawn for each specimen in Figs. 1 and 2. Gustafsson's values for copper-nickel at the corresponding temperatures are plotted for comparison in Fig. 3; for each temperature his points (crosses) lie slightly higher than the curves obtained here.

These results show, in the first place, that the Curie-Weiss law holds only within restricted ranges of temperature. When measurements could be obtained in the neighborhood of the Curie point, the curves become convex towards the T axis as is usual. At high temperatures, on the other hand, the curves become concave towards the T axis, especially for the alloys of low nickel content. The second important result is that the susceptibility at a given temperature decreases less rapidly than linearly with the addition of copper or zinc. Thus extrapolation to zero moment at 60 percent copper or 30 percent zinc is not justified. If the percent copper or zinc were plotted against average moment per nickel atom instead of moment per gram of alloy the general shape of the curves would be the same although the absolute value of the slope would decrease more rapidly with increase of copper or zinc.

In the preceding discussion of the $1/\chi - T$ curves based on the Bloch model it was mentioned that the Curie-Weiss law ought to hold best at high temperatures. Thus the curvature found for these alloys at high temperatures is not predicted by this theory. One cause for a deviation from the Curie-Weiss law could be a change in the form of the energy band at the high temperatures, due to a change in the lattice constant. When the temperature is raised and the lattice expands the band becomes narrower, causing an increase in susceptibility. The coefficient of thermal expansion of the copper-nickel alloys, at least, is known to obey the law of mixtures, increasing from the value for nickel proportionately to the percent copper added. Thus this effect would be greater in the alloys of high copper content. This is just what is found: the susceptibility at high temperatures is larger than that predicted by the Curie-Weiss law, particularly for alloys high in copper or zinc. It may be doubted, however, in view of the small total change in lattice constant, whether any such secondary effect could be important.

A second possible cause for a deviation from the theoretical curve would be a change in the number of electrons in the band. It may be possible that at higher temperatures and lower nickel contents the 4s electrons do not so readily

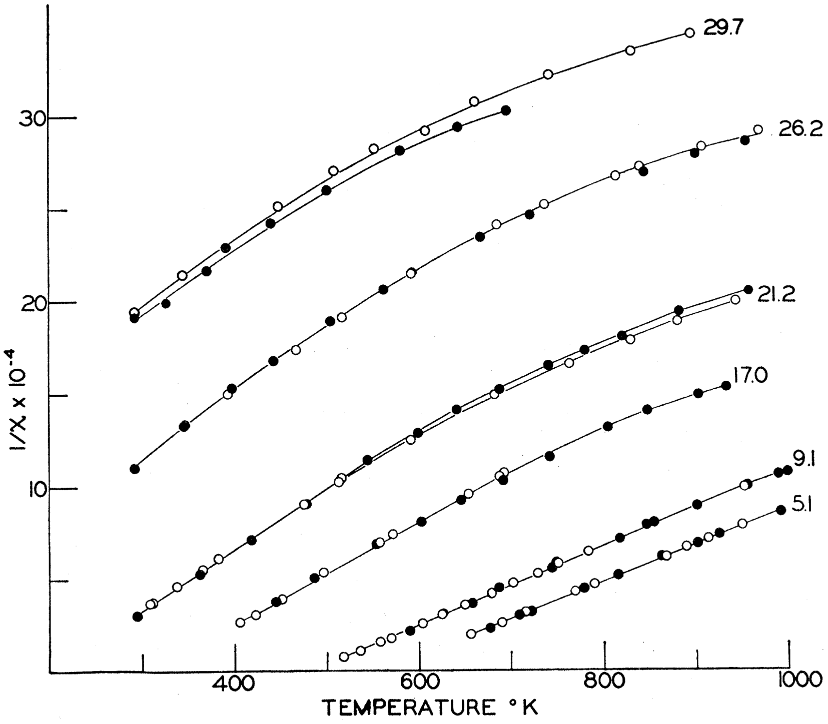

FIG. 2. Reciprocals of mass susceptibilities of ZnNi alloys plotted against the temperatures for various percents of zinc.

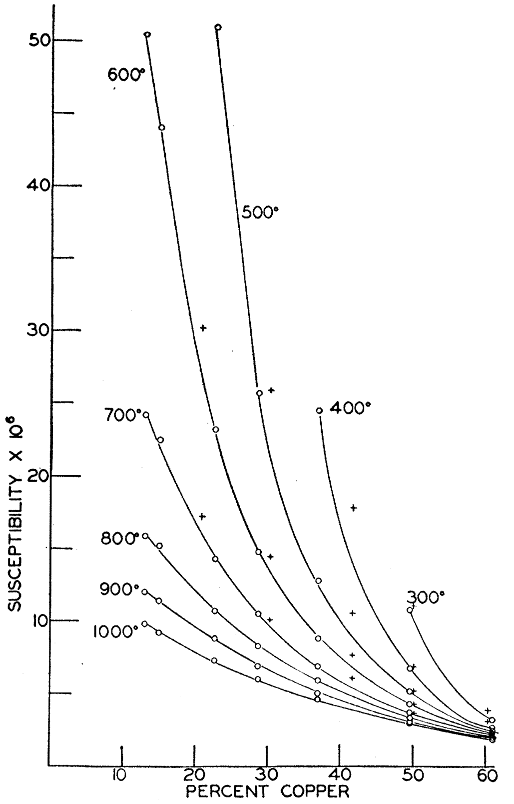

FIG. 3. Mass susceptibilities *versus* percent copper by weight for various temperatures. Gustafsson's values are indicated by crosses.

fall into the holes in the 3*d* band, with the result that in such cases the susceptibility is abnormally increased.

The second experimental result, that the susceptibility drops more slowly than in proportion to the copper or zinc content, contradicts the predictions of the Curie-Weiss law, $\chi = C/(T-\theta_p)$. By this theory in its simple form both C and θ_p are proportional to the number of paramagnetic atoms. Thus the susceptibility should decrease more rather than less rapidly than is required by a linear relation between χ and percent composition. This suggests again that the 4*s* electrons do not inevitably fill the empty spaces in the 3*d* shell, particularly at high copper and zinc content. This is difficult to reconcile with the Bloch model without special modifications. In fact the exchange interaction between the electronic spins should decrease with increased separation of the nickel atoms, resulting in a decreased value of θ and therefore a decreased susceptibility.

As yet the Heisenberg model also has not been sufficiently developed to explain either of these results satisfactorily. It should be emphasized that a linear relation between $1/\chi$ and T is not necessarily predicted by this theory. A small excess susceptibility at the high temperatures could be explained by a redistribution of the nickel atoms from d^{10} to d^9 configurations. This is, of course, comparable to the scattering of an electron from a d to an s band in the Bloch model, and is equally incalculable. Anomalous increase of susceptibility at high temperatures might also be qualitatively explained by unquenching of orbital momenta.

No predictions have been made from this point of view about the variation of the susceptibility with the percent copper or zinc added. If only the nickel atoms contribute magnetic moment, these results indicate that there may be a redistribution of the nickel atoms between the d^{10} and d^9 states with alloying. If the orbital moment is quenched due to an antiferromagnetic coupling this would decrease as the average distance between the nickel atoms increased. An added susceptibility would then result from the magnetic contribution of the orbital momenta in the alloys of low nickel content. On the other hand, as mentioned before, the ferromagnetic coupling of the electronic spins would also decrease with increased separation of the nickel atoms, causing a decrease in θ and with it a decrease in the susceptibility. Any change in the antiferromagnetic coupling or in the spin-orbit coupling would cause the gyromagnetic ratio to differ from 2. Sucksmith[15] found a g value of 1.9 at room temperature for copper-nickel alloys with Curie points around $-10°$C, which shows that the influence of the orbital momenta is not important just above the Curie point. Similar measurements on alloys with lower Curie points would be very illuminating as the orbital momenta are more apt to be liberated at temperatures well above the Curie point.

A comparison of the susceptibilities for the two sets of specimens shows that an alloy with a

---

[15] W. Sucksmith, Helv. Phys. Acta **8**, 205 (1935).

certain percent zinc corresponds most closely to the alloy with twice that percent copper. The ratio of the susceptibility of the zinc alloy to that of the corresponding copper alloy is always greater than unity but is never greater than 1.5. In general, it is higher for the alloys of low percent nickel. In other words, any factor which causes an increase in susceptibility is stronger in zinc alloys than in copper alloys having the same number of excess electrons.

No corrections for the diamagnetism of the core or for temperature independent paramagnetism were made. The atomic moment was not calculated because of the inadequacies of the Curie-Weiss law. These results agree with Gustafsson's in showing no sudden changes of slope such as were found by Alder.

The ferromagnetic Curie point was above room temperature in a few cases so that it could be measured and compared with the paramagnetic Curie point.[16] For the 15 percent copper alloy the temperature of the ferromagnetic Curie point was measured for the sample annealed for two days and for one annealed for five days. The transition from ferromagnetic to paramagnetic state was not only more gradual for the two-day sample, as already mentioned, but the value of θ_f at the point of inflection was higher for the two-day sample. The value of θ_p was the same within experimental error.

In conclusion it should be repeated that the explanation of these results is necessarily incomplete because neither the Bloch nor the Heisenberg model adequately describes the state of the alloy, and because many factors have had to be neglected in the calculations.

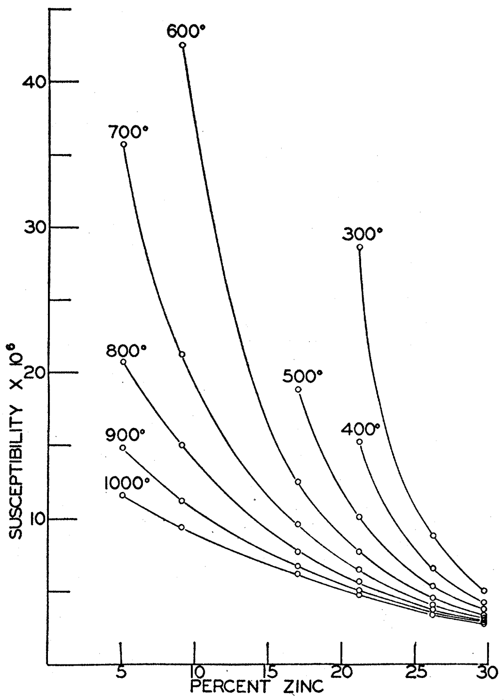

FIG. 4. Mass susceptibilities *versus* percent zinc by weight for various temperatures.

This work was done while I was a guest in the Sloane Physics Laboratory. The zinc used was the gift of Professor W. E. Milligan of the Hammond Metallurgical Laboratory of Yale. I am especially grateful to Professor L. W. McKeehan for valuable advice and encouragement and to Professor J. H. Van Vleck of Harvard for suggesting the problem and for helpful criticism.

---

[16]

	θ_f	θ_p		θ_f	θ_p
13 percent Cu	488°K	508°K	5 percent Zn	532	560
15 percent Cu	474	500	9 percent Zn	457	487
23 percent Cu	394	420			
29 percent Cu	351	370			