Temperature Dependence of the Susceptibility of Ni-Cu Alloys

V. E. Rode, A. Blyushke, S. A. Finkel'berg, and A. I. Leĭchenko

Moscow State University

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The magnetic moments of a number of nickel-copper alloys have been measured in pulsed fields up to 150 kOe at temperatures between 2 and 45°K. It is established that the temperature and field dependences of the susceptibilities of the alloys investigated are sufficiently well described by spin-wave theory.

MEASUREMENTS of the high-field susceptibility of metals and alloys at low temperatures have acquired special interest at the present time, since these measurements make it possible, on the one hand, to check the conclusions of spin-wave theory, and on the other, to obtain certain information on the density of states in the metal at the Fermi surface[1]. By the high-field susceptibility χ_{hf}, we have in mind the susceptibility of the para-process (true magnetization) in fields much greater than the field in which the contribution, determined by the magnetic anisotropy, of the rotation process becomes small compared with the contribution of the para-process.

Up to the present time, data have been given in the literature on the high-field susceptibilities of iron, nickel and certain alloys[2-7]. We have carried out measurements of the magnetic moments of a number of Ni-Cu alloys in pulsed magnetic fields up to 150 kOe in the temperature range from 2 to 45°K.

The compositions of the samples investigated and their Curie points are given in the Table. We were interested in comparing the experimental data on the high-field susceptibilities with the values predicted by spin-wave theory, and determining the exchange parameters of the alloys investigated.

The pulsed magnetic field was created by the discharge of a bank of capacitors through a multi-turn solenoid cooled by liquid nitrogen. In order to ensure stability of the magnetic-field configuration in the working volume during the time of the pulse, a system for securing the solenoid was used. The measurements were performed by means of an inductive differential detector, which made it possible to achieve high sensitivity and obtain good reproducibility of the results. Special arrangements for balancing the detector in amplitude and in phase made it possible to reduce the residual imbalance in a pulsed field of intensity 170 kOe with a pulse-front build-up of duration 30 msec to a value corresponding to a change of magnetic moment less than 0.1 Gauss. To increase the accuracy, the ferromagnetic samples were magnetized; this enabled us to avoid measuring ΔM against the background of a large initial magnetic moment. In the investigation of the temperature dependence of the high-field susceptibility, the temperature of the sample was changed by the method suggested in[10]. The relative accuracy of the measurements was 2%, and the absolute error was not greater than 10%.

The values obtained for the magnetic moment as a function of the magnetic field at different temperatures for the sample containing 45.7 at.% Ni are given in Fig. 1. From the experimental values of the field dependence of the magnetic moment, we obtained the dependence of the susceptibility χ_{hf} of the given alloys on the field H. In Fig. 2, these values are shown for three of the alloys investigated, as a function of the field at temperature 4.2°K.

Spin-wave theory gives the following temperature and field dependences of the magnetic moments[6]:

$$M(H,\,T) \approx M_0\{1 - a_{3/2}[F(3/2,\,t_H)/\xi(3/2)]T^{3/2} - a_{5/2}[F(5/2,\,t_H)/\xi(5/2)]T^{5/2}\}, \tag{1}$$

whence we can determine $\chi_{sw} = \partial M/\partial H$. Here

$$a_{3/2} = \xi\left(\frac{3}{2}\right)\frac{g\mu_B}{M_0}\left(\frac{k_B}{4\pi D}\right)^{3/2},$$

$$F(n,\,t_H) = \frac{1}{\Gamma(n)}\int_0^\infty \frac{x^{n-1}\,dx}{\exp(t_H + x) - 1},$$

where

$$t_H = g\mu_B H/k_B T,$$
$$x = Dk^2/k_B T,\quad n = 3/2,\ 5/2,$$

k being the magnitude of the wave vector of a spin wave.

We have not considered the term with $a_{5/2}$, since the errors in $a_{3/2}$ exceed the theoretically expected value of $a_{5/2}$. Besides, at the present time there are a number of measurements of the magnetic moment as a function of temperature and field[6,11], which confirm that $a_{5/2}$ amounts to less than one per cent of $a_{3/2}$.

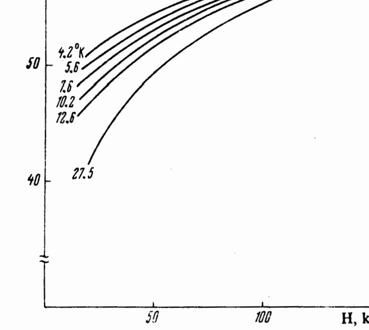

FIG. 1. Change of magnetization I of the sample (45.7 at.% Ni, 54.3 at.% Cu) as a function of magnetic field at different temperatures.

Sample*, at. %		Θ, °K	$a_{3/2}$	$(a_{3/2})^{-2/3}$	Sample*, at. %		Θ, °K	$a_{3/2}$	$(a_{3/2})^{-2/3}$
Ni	Cu				Ni	Cu			
44.0	56.0	3.8	$1.9\cdot10^{-2}$	13.8	51.3	48.7	59	$2.7\cdot10^{-4}$	238
44.2	55.8	4.5	$1.3\cdot10^{-2}$	18.1	93	7	550 [9]	$9.7\cdot10^{-6}$	2200
45.0	55.0	6.6	$7.1\cdot10^{-3}$	27.2	100	0	631	$8.8\cdot10^{-6}$ [6]	2345
45.7	54.3	15.0	$2.5\cdot10^{-3}$	54.8					

*The samples were annealed for 80 hours at a temperature of 110°C and quenched in water [8].

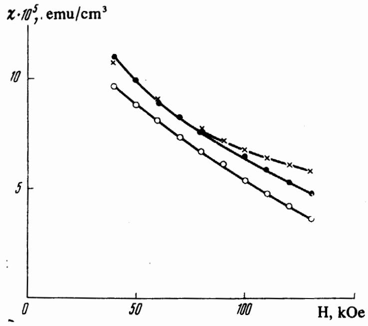

FIG. 2. Susceptibility of three of the alloys investigated as a function of the field at temperature 4.2°K: ×–44.2 at.% Ni, 55.8 at.% Cu; ●–45.0 at.% Ni, 55.0 at.% Cu; O–45.7 at.% Ni, 54.3 at.% Cu.

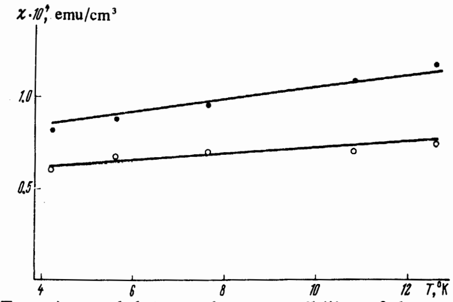

FIG. 3. Experimental data on the susceptibility of the sample (45.7 at.% Ni, 54.3 at.% Cu) as a function of temperature in different fields, together with the susceptibility curves calculated theoretically (solid lines): ●–H = 50 kOe, O–H = 90 kOe.

As is well known, a change of magnetic moment occurs not only as a result of spin excitations, but also because of the existence of certain mechanisms leading to the Pauli, van Vleck and diamagnetic susceptibilities of a ferromagnetic substance. A comparison of the experimental data with theory was therefore carried out by means of a computer using Eq. (1) and allowing for the change of the moment due to these susceptibilities[12,13]. In doing this, we regarded M_0 and $a_{3/2}$ as parameters to be determined from experiment. To determine these parameters, we used the experimental data for $M(H)|_{T=\text{const}}$.

In order to avoid the effect of the magnetic anisotropy on the susceptibility, we had to study the change of magnetic moment well above technical saturation, i.e., in fields in which the contribution from the rotation process is small compared with the contribution of the para-process.

It is known that the anisotropy constants of the alloys investigated are small compared with the anisotropy constant of nickel at low temperatures. We should expect, therefore, that for our alloys these fields do not in any case exceed the values determined for nickel, which are of order 16 kOe for polycrystalline nickel[14], and 5 kOe for a monocrystal oriented along the direction of the field[15]. To check this assumption, we processed the data twice, without considering the value of $M(H)|_{T=\text{const}}$: 1) up to H = 10 kOe; 2) up to H = 40 kOe. It should be noted that the difference between the values of $a_{3/2}$ determined in the first and second cases was found to be insignificant.

The values of $a_{3/2}$ obtained for the alloys investigated are given in the Table, with values of $a_{3/2}$ for nickel shown for comparison. The quantities $(a_{3/2})^{-2/3} \sim D$ are also shown there. With these values of $a_{3/2}$, determined from the field dependence of the magnetic moment, we calculated and constructed curves of the temperature dependence of the susceptibility of the alloys investigated. These curves are shown in Fig. 3, together with the experimental data for the susceptibilities. The parameters $a_{3/2}$ determined give good agreement between the calculated values and the experimental data. It can be concluded that, within the limits of the accuracy we attained, the spin-wave theory describes well the temperature and field dependences of the susceptibility of the Ni–Cu alloys investigated, despite the fact that the spin-wave theory was developed for ordered systems.

It seemed of interest to examine the correlation between the effective exchange integral from the spin-wave dispersion law implicitly including the dependence on the concentration of magnetic atoms, and the magnitude of the Curie temperature. The value of the parameter $a_{3/2}$ determined from the experimental data correlates with the value of the Curie temperature Θ, measured in a weak alternating magnetic field by Robbins' method[16], of the alloys investigated. If we take into account that $(a_{3/2})^{-1} \sim D^{3/2}$ (from the spin-wave dispersion law) and $\Theta \sim J_{\text{eff}}$, where J_{eff} is the effective exchange integral between the ferromagnetic electrons of the alloys, we can expect a linear dependence between Θ and $(a_{3/2})^{-2/3} \sim D$, as we have confirmed experimentally.

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