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#### SUSCEPTIBILITY AND REMANENT MAGNETIZATION OF A SPIN GLASS (\*)

#### J. L. THOLENCE and R. TOURNIER

#### C. R. T. B. T., avenue des Martyrs, BP 166, 38042 Grenoble Cedex, France

**Résumé**. — Nous définissons la gamme de concentrations dans laquelle un alliage d'impuretés de transition diluées dans une matrice noble est un verre de spins, par la possibilité de représenter ses propriétés par des fonctions universelles des variables T/c et H/c. La susceptibilité d'un verre de spins comporte une partie réversible  $\chi_r$  qui présente un maximum pointu à une température  $T_M \sim c$ . Ce maximum pointu est lié à l'apparition d'une aimantation rémanente lorsque T est inférieur à  $T_M$ . L'aimantation rémanente saturée  $\sigma_{rs}$  d'un verre de spins se représente par une courbe unique dans le diagramme réduit  $\sigma_{rs}/c = f(T/c)$ ; ses propriétés sont identiques à celles de l'aimantation rémanente de grains fins monodomaines. Nous l'interprétons en supposant qu'à  $T \ll T_M$  le verre de spins (dont les moments magnétiques distribués au hasard sont bloqués à T = 0 dans des directions aléatoires) se divise spontanément en régions contenant chacune en moyenne *n* impuretés et dont le moment résultant Mg obéit à une distribution de Gauss ( $\overline{Mg^2} = n\mu_0^2$ , où  $\mu_0$  est le moment magnétique individuel).

Abstract. — We define the concentration range where a dilute alloy of transition impurities in a noble matrix is a spin glass, by the possibility of representing its properties through universal functions of the T/c and H/c variables. The susceptibility of a spin glass contains one reversible part  $\chi_r$  which shows a sharp peak at a temperature  $T_M \sim c$ . This sharp peak is due to the presence of a remanent magnetization which appears when  $T < T_M$ . The remanent magnetization of a spin glass is represented by an universal curve in the reduced diagram  $\sigma_{rs}/c = f(T/c)$ . Its properties are like those of the remanent magnetization of monodomains. We interpret it by supposing that at  $T \ll T_M$  a spin glass (in which the magnetic moments randomly distributed are frozen at T = 0 in random directions) is spontaneously divided in regions, each one containing in average n impurities and having a resulting moment Mg described by a Gaussian distribution ( $\overline{Mg^2} = n\mu_0^2$ , where  $\mu_0$  is the individual magnetic moment).

1. Introduction. — The properties of dilute solutions of transition atoms in noble metals (CuMn, AgMn, AuFe, AuCr, AuMn...) can be understood in terms of a model, where a molecular field  $\mathcal{H}$ , is created at the site of each transition atom, due to the R. K. K. Y. interaction between the magnetic moments. In zero external field, and at T = 0, each moment is frozen in the direction of the field  $\mathcal{H}$  on its site, and only the moments in a low field are sensitive to a small excitation (magnetic field, thermal agitation) [1]. This disordered and frozen arrangement is now called a *spin glass* or a *magnetic glass* [2].

Using an idea of Blandin [3], Souletie and Tournier [4] have shown that very general properties of spin glasses may be deduced from the  $1/r^3$  decrease of the R. K. Y. interaction, and from the invariance of the product  $cr^3$  (where c is the concentration) in a dilatation model. Thus, reduced quantities such as the magnetization (M/c) and the specific heat (Cp/c)can be represented by universal functions of the reduced variables H/c and T/c (where H is the applied

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field), and the *ordering* temperatures are proportional to the concentration. These properties are observed in the <u>AgMn</u>, <u>CuMn</u>, <u>AuFe</u> systems, over large ranges of concentrations. The saturated remanent magnetization  $\sigma_{\rm rs}$  of <u>Cu-Mn</u> is also well represented by a single function in the reduced diagram :  $\sigma_{\rm rs}/c = f(T/c)$ , in the range of concentrations from 0.02 % to 2 %. This indicates that a spin glass has an intrinsic remanent magnetization.

Moreover, the theoretical study of the molecular field distribution  $P(\mathcal{K})$  enables the properties of a spin glass to be specified. In the Ising model [1, 4, 5, 6]  $P(\mathcal{K})$  leads to a specific heat (Cp) proportional to the temperature at very low temperature, with a coefficient  $(\partial Cp/\partial T) T \rightarrow 0$  independent of the concentration and to a concentration independent value of the susceptibility at T = 0. It appears that the use of the more justified Heisenberg model for the calculation of  $P(\mathcal{K})$  would give similar results [7, 8].

In this paper, we intend to define, through the study of the <u>Au</u>-Fe system, the concentration range in which an alloy has the properties of a spin-glass. The study of the initial susceptibility and of the remanent magnetization enables us to understand why

Cannella and Mydosh [9, 10] have observed a sharp maximum at  $T_{\rm M}$  in the thermal variation of the susceptibility of a spin glass measured in a small alternating field, whereas a broad maximum was generally observed by static measurements [11, 12]. Finally, we propose a macroscopic model to describe the intrinsic remanent magnetization of a spin glass, after having pointed out the similarity between its behaviour and that of the remanent magnetization of antiferromagnetic or ferromagnetic monodomains studied by L. Néel [13, 14, 15].

2. Concentration range of the spin glass behaviour. — We define an alloy to be a spin-glass in that range of concentrations where its thermal and magnetic properties can be represented by scaling laws deduced from a dilatation model [4]. This concentration range is limited at low concentration by the disappearance of the magnetic moment of an increasing fraction of transition atoms (Kondo Effect). For instance, the initial susceptibility of the <u>AuFe</u> alloys, which shows a maximum at a temperature  $T_M$ , has a value at very low temperature ( $T \ll T_M$ ) which is almost independent of the concentration between a critical concentration  $c_K$  and 1 % [16]. This value decreases, below  $c_K$ , as illustrated on the figure 1, where



FIG. 1. — The susceptibility of AuFe alloys, measured at  $T \simeq 0.05 \text{ K} < T_{\text{M}}$  is plotted versus the iron concentration.

 $(\partial M/\partial H) H \leq 160$  Oe at T = 0.05 K  $\leq T_{\rm M}$  is plotted as a function of the concentration. The value of  $c_{\rm K}$ is between 350 at. ppm and 570 at. ppm. The fraction of non-magnetic impurities (for which the susceptibility  $\chi_{\rm K}$  follows a  $1/T + T_{\rm K}$  law, where  $T_{\rm K} \simeq 0.46$  K is the caracteristic temperature of this non-magnetic behaviour) becomes important (> 0.5) below  $c_{\rm K}$  [17, 18]. We observe also (Fig. 2) that the concentration dependence of the *ordering* temperature  $T_{\rm M}$  changes around  $c_{\rm K}$ .  $T_{\rm M}$  is proportional to the concentration in the range  $c_{\rm K} - 1$  % and its variation is more rapid when c decreases below  $c_{\rm K}$ . A better definition of  $c_{\rm K}$ is obtained from the equality  $T_{\rm M} = T_{\rm K} = 0.46$  K which gives a value  $c_{\rm K} \simeq 400$  at. ppm. We have also



FIG. 2. — The concentration dependence of the ordering temperature  $T_{\rm M}$  allows to define the spin-glass range of concentrations  $(T_{\rm M} \sim c)$ , where the properties are represented by scaling laws.

plotted on this figure values of  $T_{\rm M}$  obtained from other measurements (maximum of the specific heat [4], maximum of  $\partial \rho / \partial T$  [19], appearance of a six-line Mössbauer spectrum [20, 21, 22, 23]) which may be compared to the values defined by the maximum of the initial susceptibility. In the CuMn system, the equality  $T_{\rm M} = T_{\rm K} \simeq 0.01$  K gives a value  $c_{\rm K} \simeq 5$  at. ppm which corresponds to the value where a similar decrease of the susceptibility measured at  $T < T_{\rm M}$ , was observed by Hirschkoff et al. [24]. This decrease of the susceptibility near  $c_{\rm K}$ , can be justified using a Lorentzian distribution  $P(\mathcal{K})$  of the molecular field, by supposing that all the impurities which are in a low field  $\Re$  ( $\Re < H_{\rm K}$ , where  $H_{\rm K}$  is the field necessary to induce a magnetic moment on a non-magnetic impurity) have a susceptibility  $\chi_{\rm K} \sim 1/T + T_{\rm K}$  [17, 18]. Our definition of  $c_{\rm K}(T_{\rm M} \simeq T_{\rm K})$  means that the width of the  $P(\mathcal{H})$  distribution (calculated by supposing that all the impurities are magnetic) is of the order as  $H_{\rm K}$  when  $c \simeq c_{\rm K}$ . When the concentration decreases below  $c_{\kappa}$ , the fraction of non-magnetic impurities (in a field  $\mathcal{H} < H\hat{u}$ ) becomes very important and the  $P(\mathcal{H})$  distribution is strongly modified.

For high concentrations, the properties of a dilute alloy deviate slowly from the scaling laws. The ordering temperature  $T_{\rm M}$  of AuFe is no longer proportional to the concentration when this is greater than 1 %(Fig. 2). This behaviour is justified (supposing a random distribution of the transition atoms) by the limitation of the mean free path of the conduction electrons by the solute atoms; the range of the R. K. K. Y. interaction is reduced and smaller ordering temperatures are observed [4]. Moreover the models of molecular field distributions, which explain the proportionality of the ordering temperature to the concentration, use the asymptotic form of the R. K. K. Y. interaction. This approximation is not correct when the concentration increases (c > 1. %)because then many solute atoms are near neighbours. Finally, the dilatation model, which predicts the

scaling laws, is not valid at high concentrations (c > 1 %), where the number of first neighbours and their separation are limited by the cristalline structure [4]. The *spin glass* state extends from a concentration  $c_{\rm K}$  defined by  $T_{\rm M} = T_{\rm K}$  (below  $c_{\rm K}$  the fraction of non magnetic impurities is important) to a concentration of the order of 1 % above which deviations from the scaling laws appear. We shall reserve the term mictomagnetism, introduced by Beck [25, 26, 27], for the concentrated alloys (c > 1 %) which have more complex properties than the spin-glasses. We now study the behaviour of the susceptibility of a spin glass, through the susceptibility of the <u>AuFe</u> system.

3. Reversible susceptibility of a spin glass. The thermal variation of the susceptibility measured in a small alternating field presents a sharp maximum at  $T_{\rm M}$  [9]. The susceptibility deduced from the magnetization measured by a static method, may have a different behaviour depending on the experimental conditions. Indeed, the magnetization, measured after cooling down to  $T < T_{\rm M}$  in a zero field, is reversible (no after effect and no remanent magnetization when the field is suppressed) as long as the field is smaller than a value Hm which is almost proportional to the concentration in the spin glass range of concentrations  $(Hm \sim 1\ 000\ c\ (Oe)$  for AuFe). Therefore, we can define a reversible susceptibility  $\chi_r$  by the slope  $(M(H)/H) H \rightarrow 0$  of the magnetization measured in a field H smaller than Hm.  $\chi_r$  has a thermal behaviour identical (sharp maximum) to that of the susceptibility measured by an alternative method (See AuFe 0.5 %and AuFe 0.2 % on the figure 3). When the applied field H is higher than Hm, for  $T < T_{\rm M}$ , the magne-



FIG. 3. — Thermal variation of the susceptibility deduced from first magnetization curves obtained in a field H < 160 Oe.

tization M(H) depends on the time and, when the field is suppressed, an isothermal remanent magnetization (I. R. M.) is observed. The susceptibilities, obtained either by taking M(H)/H on a first magnetization curve with H > Hm or, from a magnetization curve plotted for a field decreasing from a value higher than Hm, are larger than  $\chi_r$  (for  $T < T_M$ ) and a broad maximum is observed. Therefore a correct determination of the reversible susceptibility consists in measuring the magnetization in a field  $H \ll Hm$  such that H/c is a constant. This condition is not realized in our measurements, where, for reasons of sensibility, the magnetization is measured in a field of the order of 160 Oe. For the most dilute alloys (c < 0.2 %) this field is higher than Hm and the susceptibility presents a broad maximum around  $T_{M}$  or no maximum (see on the figure 3 the susceptibilities of AuFe 0.1 %and of more dilute alloys). Therefore, we have observed that the reversible susceptibility  $\chi_r$  obtained from the magnetization measured by a static method in a sufficiently low field (H < Hm) is the same as the susceptibility obtained by an alternative method. The existence of a remanent magnetization and of time effects are at the origine of the differences sometimes observed between these two types of measurements.

4. Remanent magnetization and irreversible susceptibility of a spin glass. — The isothermal remanent magnetization (I. R. M.) obtained after suppressing the field *H* applied at a given temperature  $T < T_M$ , is null when H < Hm; it is saturated in a field  $H_M$ almost proportional to the concentration in the spin glass state (Fig. 4). The thermoremanent magnetization (T. R. M.) measured in a zero field after cooling the sample in a field *H*, from  $T_i > T_M$  down to  $T < T_M$ , is independent of  $T_i$ ; it is proportional to *H* when this field is small, and it reaches the same saturation value than the I. R. M., but in a lower



FIG. 4. — Field dependences of the thermoremanent magnetization (T. R. M.) obtained after cooling from  $T_i > T_M$  to T = 1.2 K in a field H, and of the isothermal remanent magnetization (I. R. M.) obtained when a field H applied at 1.2 K is suppressed.

field (see Fig. 4). The magnetization M'(H) measured in a field H < Hm, applied from  $T_i > T_M$  to  $T < T_M$ , is the sum of the T. R. M. that would be measured after suppressing this field and of the reversible magnetization M(H), at this temperature T. The total susceptibility  $\chi_t$  defined by  $(M'(H)/H) H \rightarrow 0$  is then the sum of the reversible susceptibility

$$\chi_{\rm r} = \left(\frac{M(H)}{H}\right) H \to 0$$

and of an irreversible susceptibility

$$\chi_{\rm ir} = \left(\frac{{\rm TRM}(H)}{H}\right) H \to 0$$

 $\chi_t$  can be obtained indirectly, by adding the experimental values of  $\chi_r$  and  $\chi_{ir}$ , as indicated on the figure 5. We notice that  $\chi_t$  is independent of the temperature when  $T < T_M$ . The other method to obtain  $\chi_t$  consists in measuring the magnetization M'(H) in the field Happlied during the cooling. This method was used by Hirschkoff *et al.* to study the CuFe [28] and CuMn [24] systems at very low temperature. The magnetization M'(H) they measure, becomes independent of the temperature at  $T < T_M$ . These alloys have certainly a thermoremanent magnetization, and the thermal variation of their reversible susceptibility  $\chi_r$  must present a sharp maximum, similar to the one observed in AuFe.



FIG. 5. — Methods to obtain respectively the reversible  $(\chi_r)$  and the irreversible  $(\chi_{ir})$  susceptibilities, and thermal variations of  $\chi_r$  and of  $\chi_t = \chi_r + \chi_{ir}$ .

5. Properties of the remanent magnetization of a spin-glass. — The T. R. M. and the I. R. M. have the same saturation value  $\sigma_{rs}$  at a given temperature T.  $\sigma_{rs}$  can be represented, in a way similar to the magnetization and the specific heat, by a single function in the reduced diagram  $\sigma_{rs}/c = f(T/c)$ . This property, firstly shown on CuMn [4], is confirmed by our study of the AuFe system, as it is shown on the figure 6. The temperature where  $\sigma_{rs}$  reduces to zero is equal to  $T_{\rm M}$ , the temperature where the susceptibility shows a maximum. We observe (Fig. 6) scaling laws when the



FIG. 6. — Representation in the reduced diagram  $\sigma_{rs}/c = f(T/c)$  of the thermal variation of the saturated remanent magnetization  $\sigma_{rs}$  of Au-Fe alloys.

concentration lies between 0.1 % and 1 %, (that means in the spin-glass range of concentrations). Below 0.1 %, the concentration of magnetic impurities is smaller than c (Kondo effect); the remanent magnetization of AuFe 0.057 % and especially that of more dilute alloys deviate from scaling laws. When the concentration becomes higher than 1 %, the value of  $\sigma_{rs}$  at T = 0 increases more rapidly than the concentration  $((\sigma_{rs}/c) T \rightarrow 0 \text{ increases by a factor } 3$ or 4 when c goes from 1 % to 8 %) which indicates the tendancy to ferromagnetism of the concentrated alloys [29]. In a good solid solution, this tendancy is due to the ferromagnetic coupling of neighbouring iron atoms : it may be increased by segregation. We conclude that the spin-glasses have an intrinsic remanent magnetization which obeys scaling laws. Moreover the properties of the remanent magnetization of a spin-glass remind those of the remanent magnetization of ferromagnetic or antiferromagnetic monodomains studied by L. Néel [13, 14, 15], particularly :

— T. R. M. and I. R. M. have the same saturation value and they cancel out at the same  $T_{\rm M}$  temperature; then, they have the same origin. The T. R. M. is more easily saturated than the I. R. M., as for mono-domains.

— The saturated remanent magnetization decreases with the logarithm of time as it was firstly shown on <u>Au-Fe 8 % [29]</u>. These properties mean that the remanent magnetization of a spin-glass has a macroscopic origin and that there exist probably in a spin glass, regions having each one a resulting moment which is frozen in a preferential direction at very low temperature.

Before talking about the nature of such regions, let us recall some properties of the monodomains, described, by Néel [13, 14, 15].

6. Properties of monodomains (L. Néel [13, 14, 15]). — The resulting moment Mg of a monodomain is frozen at T = 0 in the direction of an anisotropy field Ha to which it is submitted. When the temperature becomes higher than the blocking temperature  $T_{\rm b}$ , this moment is free. One may associate to each monodomain a blocking energy  $\frac{1}{2}$  MgHa and a relaxation time  $\tau$  such that :

$$\tau = \frac{1}{\gamma_0} \exp\left(\frac{Mg \ Ha}{2 \ k_{\rm B} \ T}\right),$$

where  $\gamma_0$  is a characteristic frequency.

— During the cooling in a field H, from a temperature  $T > T_b$  to a temperature  $T < T_b$  the moment Mg is frozen in the direction of anisotropy making a  $\theta$  angle with the direction of H. At  $T = T_b$ , the component  $M_{\theta}$  of Mg in the direction of H is given by :

$$M_{\theta} = Mg(T_{b}) \operatorname{th} (a_{b} \cos \theta) \cos \theta$$

where  $a_b = Mg(T_b) H/k_B T_b$ . For an assembly of identical monodomains, for whoom the directions of anisotropy are randomly distributed, the mean value  $\overline{Mg}$  (for a monodomain) in the direction of the applied field is, at  $T = T_b$ :

$$\overline{Mg}(T_{\rm b}) = Mg(T_{\rm b}) \int_0^{\pi/2} \operatorname{th} \left(a_{\rm b} \cos \theta\right) \cos \theta \sin \theta \, \mathrm{d}\theta$$

and the thermoremanent magnetization, obtained at a temperature  $T < T_b$ , when the field is suppressed, is :

$$TRM(T) = \overline{Mg}(T_{b}) \times \frac{Mg(T)}{Mg(T_{b})}$$

(supposing that Mg depends on the temperature) At T = 0 and for a very low field H

TRM 
$$(T = 0) = Mg(0) \times \frac{Mg(T_b) H}{3 k_B T_b}$$

for a high field  $H(Mg(T_b) H \gg 3 k_B T_b)$ 

$$\text{TRM}(T=0) = \frac{1}{2} Mg(0)$$
.

— The blocking energy MgHa/2 of a monodomain is connected to its blocking temperature  $T_b$  by the relation :  $MgHa = (Q + \ln \tau_m) 2 k_B T_b$ , where  $\tau_m$ is the time of the measurement and Q a constant.

An assembly of monodomains having different resulting magnetic moments Mg and fields of anisotropy Ha, can be represented by a distribution in the plane (Mg, Ha) where each monodomain corresponds to a point. The monodomains having the same blocking temperature  $T_b$  are on the hyperbola  $MgHa = (Q + \ln \tau_m) 2 k_B T_b$ . The saturated remanent magnetization and its thermal dependence can be calculated, if the distribution of the monodomains in the plane (Mg, Ha) is known. The quantity Q can be deduced experimentally by the relation :

$$\left(\frac{\left(\frac{\partial \sigma_{\rm rs}}{\partial T}\right)}{\left(\frac{\partial \sigma_{\rm rs}}{\partial \ln t}\right)}\right)_{\rm T} = \frac{Q + \ln \tau_{\rm m}}{T}$$

. . .

where it is supposed that the variation  $(\partial Mg/\partial T)$  is negligible at the temperature T. Q is of the order of 22 for ferromagnetic monodomains [13].

7. Model of regions in a spin-glass. - In a spin glass, at T = 0, the individual magnetic moments, randomly distributed, are frozen in the random direction of the molecular field *H* in which they are. To explain the existence of a remanent magnetization, we shall suppose, moreover, that the alloy is spontaneously divided in independent regions to minimize its energy. This is due to the existence of a uniaxial anisotropic energy which was not taken into account to calculate the microscopic properties of a spin glass, from a  $P(\mathcal{K})$  distribution. Then, the individual magnetic moments, coupled by the R.K.K.Y. interaction are inside such regions. At T = 0, the resulting magnetic moment of each region is frozen in the direction of its anisotropy axis. These resulting moments give rise to the irreversible properties, the individual magnetic moments, in low molecular fields, participate to the reversible properties.

To simplify, let us suppose that the *n* magnetic moments of a region are only parallel or antiparallel (Ising model). In this case, considered by Néel [15], the moment Mg of a region, is due to the imperfect compensation of the moments of opposite directions. If the value of this moment obeys a Gaussian distribution law its mean square value  $Mg^2$  is equal to  $n\mu_0^2$  (where  $\mu_0$  is the magnetic moment of each transition atom), and the average of the absolute value of the resulting moment is  $(2 n/\pi)^{1/2} \mu_0$ . The saturated remanent magnetization  $\sigma_{rs}$  of such a system is obtain ed at T = 0, when the moment of each region is oriented on the axis of anisotropy, along the direction nearest to that of the applied field H(Mg.H > 0). It is then given by :

$$\sigma_{\rm rs}(T = 0) = \frac{N_0}{2} \left(\frac{2 n}{\pi}\right)^{1/2} \mu_0$$

where  $N_0$  is the number of regions containing in average *n* impurities.

The saturated magnetization  $\sigma_s$  the alloy would show, would than be  $\sigma_s = N_0 n\mu_0$ . The number *n* is easily determined from these two relations :

$$n = \frac{1}{2 \pi} \left( \frac{\sigma_{\rm s}}{\sigma_{\rm rs}} \right)^2$$

In the case of AuFe the value of n is almost independent of the concentration ( $\sigma_s$  and  $\sigma_{rs}$  are proportional to c), it varies from 510 to 330 when c goes from 0.1 % to 1 %, by using  $\mu_0 = 2 \mu_B$ . In the CuMn system, with  $\mu_0 = 4 \mu_B$ , we obtain n = 255 independent of the concentration in the spin glass regime.

The Curie constant C' that would be observed for these  $N_0$  regions in the superparamagnetic state:  $C' = N_0 n \mu_0^2 / 3 k_B$  is smaller by a factor  $(\mu_0 / \mu_{eff})^2$ than the Curie constant of  $N_0 n$  paramagnetic moments C' can be compared to the superparamagnetic constant calculated from experimental data on the remanent magnetization and its thermal dependence near T = 0, by supposing uniform distributions of Mg $(0 < Mg < M_M)$  and of Ha (between Hm previously defined, and the field of saturation  $H_M$  of the remanent magnetization), and by using the value  $Q \simeq 15$ determined for AuFe 8 % [29]. This comparison is in favour of the model of regions [17, 18].

The origin of the anisotropy giving rise to regions in a spin-glass, is certainly a type of interaction decreasing as  $1/r^3$ , this, in order to explain a remanent magnetization represented by scaling laws. The dipolar interaction or an anisotropy of the R. K. K. Y. interaction can explain the existence of such regions. The dimensions of a region are such that the mean field created on the site of an individual magnetic moment by the anisotropic interaction with the other moments inside the region, is equal to the mean field due to the R. K. K. Y. coupling with the moments outside. The values of *n* determined for <u>AuFe</u> and <u>CuMn</u> are compatible with the relative intensities of the dipolar interaction and of the R. K. K. Y. interaction.

All the properties of a spin-glass may be deduced from a model where the solute atoms are randomly distributed and where the magnetic moments are randomly frozen at T = 0, after a zero field cooling. The irreversible properties of a mictomagnetic alloy are similar to those of a spin glass, (the magnetization measured in the field H after a zero field cooling down to  $T < T_{\rm M}$  is smaller than the magnetization obtained in the same field H applied during the cooling [26]but they diverge progressively from scaling laws when c increases. In these alloys, even in the case where the solute atoms are quite randomly distributed, a number of magnetic moments are not randomly oriented on account of the ferromagnetic or antiferromagnetic interactions between near neighbours. The properties of a mictomagnetic alloy are more complex than these of a spin-glass.

8. Conclusion. — An alloy of magnetic atoms dilute in a noble host is called spin glass when its reduced properties  $(C_p/c, M/c...)$  can be represented by universal functions of H/c and T/c. The concentration range where this is verified is limited by a lower value  $c_{\rm K}$  (defined from the equality  $T_{\rm M} = T_{\rm K}$  where  $T_{\rm M}$ is the temperature at which the susceptibility presents a maximum, and  $T_{\rm K}$  is the Kondo temperature) below which the disappearance of the magnetic moment of an increasing fraction of solute atoms is observed [17, 18]. When the concentration becomes higher than 1 %, and even in a good solid solution, the properties of the alloys diverge progressively from scaling laws. The interactions between near neighbors become numerous, and the magnetic moments are less and less randomly oriented. These concentrated

alloys, where the precipitation may increase the ferromagnetic and antiferromagnetic clusters are called mictomagnetic alloys.

The susceptibility of a spin glass contains a reversible part  $\chi_r$  obtained either by a measure in a low and alternating field [9], or by a static method, from the magnetization curve determined in a field H smaller than a value Hm proportional to c, above which irreversible phenomenons appear. The thermal variation of  $\chi_r$  shows a sharp maximum at  $T = T_M$ . On the contrary, the magnetization M'(H) measured after cooling (from  $T > T_M$  to  $T < T_M$ ) in a low field H, and the susceptibility defined by

$$\chi_{\rm t} = \left(\frac{M'(H)}{H}\right) H \to 0$$

are independent of the temperature below  $T_{\rm M}$ . We observe that  $\chi_{\rm t}$  is the sum of  $\chi_{\rm r}$  and of an irreversible susceptibility  $\chi_{\rm irr}$  given by the variation

$$\left(\frac{\partial \mathbf{TRM}}{\partial H}\right)H \to 0$$

of the thermoremanent magnetization obtained after cooling in the field H. The sharp maximum presented by the thermal variation of  $\chi_r$  is correlated to the appearance of a remanent magnetization below  $T_{\rm M}$ . When the susceptibility is not measured cautiously (H < Hm), values between  $\chi_r$  and  $\chi_t$  are obtained at  $T < T_{\rm M}$  and a broad maximum is observed.

The saturated remanent magnetization  $\sigma_{rs}$  of spinglasses is well represented by scaling laws

$$\left(\frac{\sigma_{\rm rs}}{c} = f\left(\frac{T}{c}\right)\right),\,$$

then it is an intrinsic property of the spin-glasses due to an interaction decreasing as  $1/r^3$ . It presents properties which are similar to the properties of monodomains [13, 14, 15, 29], indicating that the remanent magnetization of a spin glass has a macroscopic origin. From these properties, we conclude that a spin-glass (where the magnetic moments are randomly distributed and frozen in random directions at T = 0) is spontaneously divided at T = 0 in regions, this, because of an anisotropic interaction decreasing as  $1/r^3$ . Each region containing about n solute atoms has a resulting moment Mg such that  $\overline{Mg^2} = n\mu_0^2$ . One may deduce from  $\sigma_{rs}$  and from the saturated magnetization  $\sigma_s$  a value of *n*, which is almost independent of the concentration, and the superparamagnetic Curie constant C' that these regions would have if they were not destroyed at higher temperatures. C' corresponds quite well to the value which can also be independently calculated from the thermal variation of  $\sigma_{rs}$ , by supposing uniform distributions of Mg and Ha; it corresponds also, with the factor  $(\mu_0/\mu_{eff})^2$  to the paramagnetic Curie constant observed at  $T \gg T_M$ .

The presence of ferromagnetic clusters in more concentrated (mictomagnetic) alloys leads to more complex properties.

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#### References

- [1] BLANDIN, A. and FRIEDEL, J., J. Phys. & Radium 20 (1959) 160.
- [2] ANDERSON, P. W., Mat. Res. Bull. 5 (1970) 549 and COLES, B. R. in reference in this paper.
- [3] BLANDIN, A., Thesis, University of Paris (1961).
- [4] SOULETIE, J., Thesis, University of Grenoble (1968).
  SOULETIE, J. and TOURNIER, R., J. Low Temp. Phys. 1. (1969) 95.
- [5] MARSHALL, W., Phys. Rev. 118 (1960) 1520.
- [6] KLEIN, M. W. and BROUT, R., Phys. Rev. 132 (1963) 2412.
- [7] KLEIN, M. W. to be published in « Proceedings of the 13th Int. conf. on Low Temp. Phys. Boulder, Colorado (1972).
- [8] RIVIER, N. and ADKINS, K. Proceedings of the International Symposium on Amorphous Magnetism: Amorphous Magnetism (Edited by H. D. Hooper and A. M. de Graaf, Department of Physics, Wayne State University, Detroit, Michigan) 1973, p. 215.
- [9] CANNELLA, V. and MYDOSH, J. A., Phys. Rev. B 6 (1972) 4220.
  - CANNELLA, V. and MYDOSH, J. A., Conference on Magnetism, Denver (1972).
- [10] CANNELLA, V., Proceedings of the International Symposium on Amorphous Magnetism: Amorphous Magnetism (Edited by H. D. Hooper and A. M. de Graaf, Department of Physics, Wayne State University, Detroit, Michigan) 1973, p. 195.
- [11] LUTES, O. S. and SCHMIDT, J. L., Phys. Rev. A 134 (1964) 646.
- [12] THOLENCE, J. L. and TOURNIER, R., J. Physique 32 (1971) C1-211.

- [13] NÉEL, L., Ann. Géoph. 5 (1949) 99.
- [14] NÉEL, L., Physique des Basses Températures (Gordon and Breach New York) 1961.
- [15] NÉEL, L., Cours de Physique Théorique, les Houches (1961) (Presses Universitaires de France, Paris).
- [16] DREYFUS, B., SOULETIE, J., THOLENCE, J. L. and TOURNIER, R., J. Appl. Phys. **39** (1968) 846.
- [17] THOLENCE, J. L., Thesis, University of Grenoble (1973).
- [18] THOLENCE, J. L. and TOURNIER, R., to be published.
- [19] MYDOSH, J. A., KAWATRA, M. P., BUDNICK, J. I., KIT-CHENS, T. A. and BORG, R. J. in Proceedings of the 11th. Conference on Low Temperature Physics (St Andrews University, Printing Department, St Andrews, Scotland) 2 (1969) 1324.
- [20] BORG, R. J., BOOTH, R. and VIOLET, C. E., Phys. Rev. Lett. 11 (1963) 464.
- [21] CRAIG, P. P. and STEYERT, W. A., Phys. Rev. Lett. 13 (1964) 802.
- [22] GONSER, V., GRANT, R. W., MEECHAM, C. J., MUIR, A. M. and WIEDERSICH, H., J. Appl. Phys. 36 (1965) 2124.
- [23] VIOLET, C. E. and BORG, R. J., Phys. Rev. 149 (1966) 560.
- [24] HIRSCHKOFF, E. C., SYMKO, O. G. and WEATHLEY, J. C., J. Low Temp. Phys. 5 (1971) 155.
- [25] BECK, P. A., Met. Trans. 2 (1971) 2015.
- [26] BECK, P. A., J. Less Common Metals 28 (1972) 193.
- [27] BECK, P. A., Magnetism in Alloys, Editors Waber J. T. and Beck, P. A. (T. M. S., AIME) 1972.
- [28] HIRSCHKOFF, E. C., SHANABERGER, M. R., SYMKO, O. G, and WHEATLEY, J. C., J. Low Temp. Phys. 5 (1971) 545.
- [29] TOURNIER, R., Thesis, University of Grenoble (1965).