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Hysteresis in CuMn :
The effect of spin orbit scattering on the anisotropy in the spin glass state

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Résumé. — L’étude des cycles d’hystérésis à 1,45 K de systèmes ternaires Cu-Mn1% -Au dans l’état verre de spins montre que la largeur du cycle est proportionnelle à la concentration d’or avec un taux d’accroissement de 6,2 ± 0,4 kOe/at. % Au. Le fait que ce taux d’accroissement soit beaucoup plus faible pour les systèmes Cu-Mn1%-Agx et Cu-Mn1%-Alx et plus grand pour le système Cu-Mn1%-Ptx montre sans ambiguïté que le couplage spin orbite est responsable de l’anisotropie macroscopique dans l’état verre de spin. La comparaison est faite avec des alliages similaires étudiés en RPE par Okuda et Date et quelques conséquences sont discutées.

Abstract. — Measurements of the hysteresis cycle of the magnetization of CuMn 1 % in the spin glass state as a function of the concentration of a non magnetic impurity show that the width of the hysteresis is proportional to the concentration of Au at a rate of 6.2 ± 0.4 kOe/at. % Au. A much smaller rate observed for Al and Ag and higher rate observed for Pt demonstrate unambiguously that the spin orbit interaction is responsible for the anisotropy field in the spin glass state. A comparison is made with similar alloys studied by spin resonance by Okuda and Date and some implications are discussed.

1. Introduction. — The properties of the magnetization along a complete hysteresis loop in a spin glass have been investigated rather thoroughly for CuMn and AgMn by Kouvel [1] for a range of concentrations above 5 % Mn. Only recently the more dilute alloys of CuMn have been studied by Monod, Prejean and Tissier [2] down to 0.06 % Mn. In this work [2] additional references to previously published hysteresis cycles for CuMn and AgMn are available. Very few other systems have been reported so far, except in a very sketchy manner, from which only qualitative conclusions can be drawn. These concern AuFe [3], CrFe [4], PdMn [5], Mn aluminosilicates [6] and AuCo [3]. One of the major conclusions of refs. [1] and [2] was, however, that despite the very close, almost quantitative, similarity of the magnetization properties of CuMn (and AgMn) on one hand and AuFe on the other hand, there was a striking difference in behaviour between these two systems when a hysteresis loop was measured. In order to emphasize this, a comparison is made in figure 1 of hysteresis cycles for CuMn 8 % and AuFe 8 % ref. [3] measured in similar conditions at 4.2 K. As is evident the system AuFe has a very smooth symmetrical and featureless hysteresis loop. This fact is best interpreted [3] in terms of a distribution of magnetically hard microdomains, stabilized in their own anisotropy field : in this model the width of a few kilogauss of the cycle is a measure of the width of the distribution of the anisotropy field in the spin glass state. A comparison is made with similar alloys studied by spin resonance by Okuda and Date and some implication are discussed.
in the same spirit, that only those systems that yield readily observable electron spin resonance in the spin glass state (i.e. CuMn, AgMn and PdMn) had such a very steep magnetization reversal at low negative fields in their hysteresis cycles. This correlation provides a quantitative definition of what is meant by free in terms of the width of the electron spin resonance signal. A straightforward test of this conjecture then consists in measuring the effect on the hysteresis of an impurity already known for its strong spin flip scattering effect. As a first choice we have selected Au as it is supposed to introduce the least electronic disturbance when replacing a Cu atom. The following is an account of our observations and comparison with similar tests made with other impurities with little spin orbit coupling (Al or Ag) or a larger one (Pt).

2. Experimental results. — 2.1 Sample preparation and experimental technique. — The samples were prepared by melting the constituents with a semilevitation induction furnace and by quenching the melt in a rotating cylindrical copper mold [8].

The copper and non magnetic impurities are first melted under $10^{-6}$ torr, a second melting under argon is necessary to include the manganese and a third one to insure homogeneity and permit quenching of the melt. The alloys CuMn$_{8\%}$, Au$_x$, were studied first in the as quenched condition and subsequently after annealing at 900°C in Ar + H$_2$ atmosphere for one hour followed by a slow cooling. The alloys CuMn$_{8\%}$Al$_x$, CuMn$_{8\%}$Ag$_x$, CuMn$_{8\%}$Pt$_x$ were studied only in the quenched condition. For the magnetic measurements the same procedure is used for all samples as follows: the alloy is first cooled under a field of 18 kOe from well above the spin glass temperature (approximately 10 K for CuMn$_{8\%}$) down to 1.45 K. At this temperature the field is removed and the sample is left with a so called (saturated) remanent magnetization $\sigma_r$ in zero field. To avoid any stray field from the superconducting coil used to create the remanent magnetization, the sample is further lowered into the measuring section of the apparatus where a magnetic field of ± 3 500 Oe parallel to the cooling field can be achieved by a nitrogen cooled copper coil. As explained in ref. [2] the magnetization is measured by the extraction method: the sample is mechanically moved between the centres of two counterwounded pick-up coils whose flux variation is integrated by a ballistic galvanometer associated with a recorder. The sensitivity of the system is of the order of $10^{-5}$ emu, and because of the finite time constant of the galvanometer circuit (about 20 s) it can be left integrating at all times. Thus this system will be able to record not only actual flux changes due to the mechanical extraction of the sample but also flux variations due to spontaneous magnetization changes within the sample (without extraction) provided that the time constant of these changes would be somewhat shorter than 20 s.

2.2 CuMn results. — The specific hysteresis properties of CuMn (at low concentration) have been described in ref. [2]. We will only recall here how these have been analysed. Figure 2 represents the hysteresis cycles of a CuMn$_{8\%}$ well annealed (solid squares) and as quenched (solid circles) at 1.45 K. Both have common features: the measured magnetization is composed of two parts: the remanent magnetization $\sigma_r$ and the induced or reversible magnetization which is linear with field. Thus:

$$M = \sigma_r + \chi(T) H$$  \hspace{1cm} (1)

where $\chi(T)$ is by definition the reversible susceptibility. It is apparent that this relation is followed for negative values of $H$ until a value $H_r$ (of about −170 Oe) where a sudden reversal of $\sigma_r$ in one step (or a limited number of steps) occurs. For small variations of field beyond $H_r$ or coming back towards zero field from this point, the variation of $M$ is represented by:

$$M = -\sigma_r + \chi(T) H.$$  \hspace{1cm} (2)
However on the way back this is followed only until another threshold field (about 0 Oe in our case) is reached. At this point the remanent magnetization is seen to switch back to a value close to its initial value. This remarkably simple behaviour can be parametrized by the width $\Delta H$ of the hysteresis cycle and the position of the centre of the cycle for either the quenched or annealed CuMn$_1\%$ in figure 2.

It appears that the only effect of quenching is a broadening of the tail of the cycle. It should be noted however that the initial sharp drop of magnetization occurs at the same field $H_r$ and that neither the reversible susceptibility nor the value of the remanent magnetization have changed in any significant manner in both states of the alloy [9].

2.3 CuMn$_{1\%}$Au$_x$ system. — We have studied the hysteresis of CuMn$_{1\%}$Au$_x$ with concentrations of $x = 3\%, 1\%, 0.3\%, 0.1\%, 0.03\%$ and $0.01\%$. When comparing the results of the lowest Au concentration alloys in the as quenched condition and the annealed condition the same qualitative difference appeared in the hysteresis loops when measured as for the CuMn$_{1\%}$ discussed above. That is why we will only present the results of the annealed alloys.

Figure 3 represents the ensemble of magnetization curves measured at 1.45 K along the first branch of the hysteresis cycle for these alloys. As will be made clear, the effect of Au impurities on CuMn$_{1\%}$ is very specific depending upon which property is investigated: this effect is very apparent on what we loosely term dynamical magnetic properties, and to the contrary it is not measurable from the static or quasi-static magnetic properties. In order to describe these effects in a systematic way, we first present the properties that are apparently unmodified by the presence of Au and then those that do depend on the presence of Au impurities.

a) Unmodified quantities. — The examination of figure 3 and table I reveals that within $\pm 10\%$ (which is the accuracy attributed to the experimental procedure [10]) neither the remanent magnetization $\sigma_r$, nor the reversible susceptibility $\chi$ are affected by the presence of gold in the concentration range 0.01 $\%$ - 3 $\%$ at 1.45 K. In order to check more precisely this fact, on CuMn$_{1\%}$ and CuMn$_{1\%}$Au$_{1\%}$, we have compared with much more care the temperature and time dependence of the saturated thermoremanent magnetization $\sigma_r(T, \log t)$ on one hand, and the hysteresis cycle in large fields on the other hand. As shown on figure 4 at $T = 1.48$ K and $T = 4.2$ K we do not...
Table 1.

<table>
<thead>
<tr>
<th></th>
<th>CuMn1%</th>
<th>CuMn1%Au1%</th>
<th>CuMn1%Au1%Al1%</th>
<th>CuMn1%Pt0.1%</th>
<th>CuMn1%Ag1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>0</td>
<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>0.25</td>
<td>0.22</td>
<td>0.21</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>$(10^{-3} \text{ rem}(\text{g}))$</td>
<td>2.85</td>
<td>2.84</td>
<td>2.79</td>
<td>2.89</td>
<td>2.95</td>
</tr>
<tr>
<td>$H_r$</td>
<td>-170</td>
<td>-216</td>
<td>-352</td>
<td>-529</td>
<td>-802</td>
</tr>
<tr>
<td>$(\text{rem}(\text{g}))$</td>
<td>-382</td>
<td>-470</td>
<td>-882</td>
<td>-1000</td>
<td>-1200</td>
</tr>
<tr>
<td>$H_r^{(2)}$</td>
<td>32±0</td>
<td>28±0</td>
<td>44±0</td>
<td>80±0</td>
<td>100±0</td>
</tr>
<tr>
<td>$K = \frac{k_B H_r}{(\text{erg/mole Cu})}$</td>
<td>70</td>
<td>101</td>
<td>140</td>
<td>237</td>
<td>338</td>
</tr>
</tbody>
</table>

(*) Remanent magnetization at $T = 1.45 \pm 0.15$ after cooling in 18 kG.
(1) Reversibility susceptibility $dM/dH$ around zero field.
(2) Reversal field for the first step in the magnetization hysteresis (see text) and figures 3, 6a, 6b.
(3) Back reversal field observed on the negative branch of the hysteresis cycle of the remanent magnetization. The ± sign encloses the range of field over which the major part of the magnetization switch back to the positive (original) branch of the hysteresis cycle. This part of the cycle is present in figure 2 but has been systematically dropped (for sake of clarity) in figures 3, 6a, 6b.
(4) Anisotropy energy in erg/mole. In order to express this in erg/cm$^3$, × the figure by 0.14.

detect to within ±0.5% any sizeable difference either on the value of $\sigma_1$ (taken at 1 min. after removing the field), or on the further time dependence of $\sigma_1$ during the first hour at these two temperatures.

We have also checked that the first magnetization curve $M(H)$ (after cooling in zero field) at 1.45 K is identical for CuMn1% and CuMn1%Au1% to within ±1%. In the same way the magnetization $M(H)$ measured in decreasing fields from 20 kOe down to zero is identical for both alloys also within ±1%.

b) Effects of Au impurities. — The main point is the following: the effect of Au impurities in CuMn1% is a very large increase of the reversal field $H_r$ with Au concentration at a rate of

$$6 \, 200 \pm 400 \, \text{G/} \% \, \text{at. Au},$$

as is shown in figure 5 where the field $H_r$ defined by the initial drop of magnetization in figure 3 is plotted versus Au concentration.

Furthermore, the effect of increasing the concentration of Au is observed to considerably lengthen the time constant of the magnetization reversal. This property gives rise to some experimental difficulties. As we pointed out previously[2], the order of magnitude of the time constant of the magnetization jumps is 1 s or less for the CuMn system ($c < 2\%$).

For the lowest concentrations of gold ($x < 0.06\%$), we are able to detect the occurrence of the jump, because it is sufficiently rapid to induce a sizeable flux variation in our detection coil. For these samples, as soon as such a flux variation is detected, we keep the magnetic field $H_r$ constant and we measure the magnetization of the sample with time. We observe that $M(H_r)$ after this initial rapid drop continues to decrease with time much faster than the well-known logarithmic time variation of the isothermal and thermoremanent magnetizations.

For higher gold concentration ($x \geq 0.1\%$), we could not observe any rapid magnetization drop. In order to still be able to detect such a slow reversal of magnetization, we tested the logarithmic time decay of magnetization for different negative fields. For a given negative field, we notice that the magnetization decreases much faster than the time variation expected. We take this as a criterion for the beginning of a slow reversal of magnetization. For example, we observed that the remanent part of the magnetization of CuMn1%Au0.15% is half inverted in 200 min. During the same time, the logarithmic time variation of the isothermal and thermoremanent magnetization is of the order of a couple percent.

Fig. 5. — $H_r$ versus $x$ for Pt, Au, Al, at 1.45 K. $H_r$ is the negative field where we observe an initial drop of magnetization (Figs. 3, 6a, 6b). On figure 5a we represent the effect of Al by a dashed line extrapolated from result of 1, 2 and 3% Al. See the corresponding cycles in figure 6a.
For the highest gold concentrations (0.3 %, 1 %, 3 %), the time constants of a possible reversal of magnetization become of the order of the time constants involved in the ordinary time dependence of the isothermal and remanent magnetization. So it becomes experimentally impossible to determine any reversal of magnetization. In this case it is possible to measure a so-called classical remanent magnetization hysteresis cycle [7] as in AuFe [3]. We did not find at 1.45 K any notable difference between the remanence cycles of CuMn₁%Au₁% and CuMn₁%Au₂%.

When a magnetization reversal is observed, it is possible to study the dynamics of this reversal with time. It is seen to obey a complex behaviour initially with a time dependence characterized by a logarithmic law (during a time (200 s to 1 000 s) the longer the lower the Au concentration) and then in a second regime following the rapid change the evolution more closely follows an exponential behaviour with a large time constant. So, a long time after the beginning of the reversal of magnetization, it is difficult to distinguish this dynamical feature from the ordinary time variations of the isothermal and remanent magnetization.

The third point we want to emphasize is that, for the alloys where we could detect a reversal of magnetization, when coming back along the second (lower) branch of the hysteresis cycle (not represented on figure 3) there is a tendency to switch back in the same region of field near zero field (see table I H_r (back)). This field depends on the amplitude of the previous excursion made in negative fields (we have not studied this in detail however). We conclude that both the width \( \Delta H \) and the displacement field \( H_d \) of the cycle have the same linear Au concentration dependence as \( H_r \).

In good agreement with our earlier findings, we found for CuMn₁%Au₀.₀₁% at 1.45 K and 2.17 K that the product \( \sigma(T)H_r(T) \) is temperature independent and that the switch back of the magnetization occurs for both temperatures at \( H \sim 0 \). That reflects that for our alloy \( \sigma \Delta H \) is a constant and that the width of the cycle increases as the remanent magnetization decreases.

2.4 CuMn₁%Ix SYSTEMS (I = Ag, Al, Pt). — We have studied the hysteresis of CuMn₁%Ag₀.₅%, CuMn₁%Alₓ (\( x = 1 \% \), 2 %, 3 %), CuMn₁%Ptₓ (\( x = 47 \pm 3 \) ppm, 100 ± 3 ppm, 300 ppm). Figures 6a and 6b represent the hysteresis results obtained at 1.45 K, for these as quenched samples.

We find that the properties just described above for CuMn₁%Auₓ are also qualitatively found for these systems. In particular the distinction between unmodified properties and alloy dependent properties still holds. As evident from figures 6a and 6b, the value of the reversible magnetization slope and of the remanent magnetization is independent of Ag, Al or Pt in the range of concentration used. However the increase of the reversal field \( H_r \) is observed to be very specific to the impurity present. In particular the effect on \( H_r \) of Ag impurities is, if it exists, very small and we only can infer a maximum value for the rate of increase of the reversal field by Ag (Table I).

The enhancement of \( H_r \) with increasing Al and Pt concentrations is represented on figures 5a and 5b. In figure 5a for comparison we indicate the extrapolated (dashed line) linear dependence of \( H_r \) on \( x \) for CuMn₁%Alₓ. In figure 5b the extrapolation from the CuMn₁%Auₓ data is shown. The difference in the slope \( \Delta H_r/\Delta x \) is more than 2 orders of magnitude
when comparing the effects of Al and Pt impurities. We shall discuss below the significance of such a difference.

2.5 OTHER SYSTEMS. — As we noticed, addition of Ag impurities in CuMn$_{1\%}$ did not bring a sizeable effect on the value of the reversal field. The hysteresis cycle of a single crystal of AgMn$_{1\%}$ (Fig. 7) at 1.6 K exhibits a behaviour similar to that of CuMn$_{1\%}$. We can compare the remanent magnetization $\sigma_r$ and the reversible susceptibility $\chi$ from the available data for CuMn$_{1\%}$ at 1.45 K and AgMn$_{1\%}$ at 1.6 K; but we know [11] that $\sigma_r$ and $\chi$ are functions of the reduced temperatures $T/T_\gamma$ (where $T_\gamma$ is the temperature of the maximum of the susceptibility), and as the values of $T_\gamma$ differ for these samples (~ 5 K for AgMn$_{1\%}$, ~ 10 K for CuMn$_{1\%}$) the reduced temperatures $T/T_\gamma$ also differ (~ 0.14 for CuMn$_{1\%}$, ~ 0.32 for AgMn$_{1\%}$). We noticed before that $H_r$ was temperature dependent but that the product $\sigma_r H_r$ was nearly independent on the temperature. So, rather than comparing the reversal fields for CuMn$_{1\%}$ and AgMn$_{1\%}$, it is more relevant to compare the product $\sigma_r H_r$ per mole:

$$\sigma_r H_r (\text{AgMn}_{1\%}) = 590 \pm 50 \text{ erg/mole Ag}$$

$$\sigma_r H_r (\text{CuMn}_{1\%}) = 280 \pm 30 \text{ erg/mole Cu} .$$

In a preliminary experiment, we measured a AgMn$_{1\%}$ sample obtained by melting the constituents for a few hours in an alumina crucible in an electric furnace. We could not detect any reversal of magnetization. The CuMn alloys prepared in the same manner and studied by Tournier [8] also did not exhibit any reversal of magnetization. We know [3] that such a metallurgical preparation introduces in the samples some impurities, iron in particular. We believe that the presence of some ppm of these iron impurities are responsible of the disappearance of any detectable reversal of magnetization.

3. Discussion. — In order to discuss our results in terms of an anisotropy field and anisotropy energy of the CuMn spin glass phase, we first briefly recall how these quantities are introduced at an elementary level in the discussion of the magnetostatic properties of a single, isolated magnetic particle. This is presented in far greater detail in the classical work of Stoner and Wollfarth [12], Néel [13] and subsequently M. F. Brown [14] who used this analysis to interpret the hysteresis properties of hard magnetic materials. For a homogeneously magnetized spherical particle of moment $M$, possessing an uniaxial anisotropy energy $K$ (of unspecified origin) in the presence of an external field $H$ applied parallel to the anisotropy axis, the magnetic energy $E$ is only a function of the magnetization angle $\theta$ with respect to the field (and anisotropy axis):

$$E = K \sin^2 \theta - MH \cos \theta .$$

The stability condition $dE/d\theta = 0$ gives the equilibrium positions $\theta_{eq} = 0, \pi$. The metastability condition:

$$\left| \frac{d^2E}{d\theta^2} \right|_{\theta = \theta_{eq}} \geq 0$$

gives the range of field over which both equilibrium points are locally stable. Defining the anisotropy field $H_A$ by $K = 1/2 M H_A$ leads to:

$$-H_A < H < +H_A .$$

In this picture the hysteresis cycle is thus a square of height $2M$ and of width $\Delta H = 2H_A$, centred at $H = 0$. We have shown in ref. [2] how this model can be applied for CuMn in the spin glass phase for describing the effect of a number of variables such as the magnetization amplitude, the field direction (in presence of a transverse field), the Mn concentration, the temperature and the sample preparation. The major conclusion was that whereas a hard ferromagnetic material can be considered as the juxtaposition of a wide distribution of such magnetic particles at a microscopic level (with generally poorly specified interactions) it appeared that the spin glass phase of CuMn had the properties of a single magnetic particle over a macroscopic sample. Furthermore, it was shown that the demagnetizing field was two orders of magnitude smaller than the anisotropy field, thus justifying the absence of domains or shape effects in our analysis. As we wish to extend this work to the present situation, a difficulty arises for the analysis of the hysteresis cycles shown in figure 3 for a concentration of Au above 0.1 % where the cycle can no longer be considered as a simple square. Indeed, as explained in the experimental section, only the
first instability can be well defined, but the associated magnetization reversal amplitude corresponds to a smaller and smaller fraction of the remanent magnetization as the Au concentration increases and the time constants involved become very long. Of course a natural way of defining the anisotropy energy would consist of taking it equal to 1/8 of the area of the hysteresis cycle, whatever its shape. We have not done this as this would take into account that part of the hysteresis cycle in large negative field where we think the magnetization proceeds with IRM type processes rather than by large scale remanent magnetization reversal. However there is at present no clear criterion to distinguish between these two mechanisms when their effect become comparable. Instead, we have retained as a single characteristic parameter the reversal field \( H_r \) at which the first instability occurs, i.e. assuming explicitly that all the magnetization should be reversed when waiting a long enough time at \( H_r \). With this very important restriction we can proceed to evaluate the anisotropy energy for each Au concentration. Taking into account the observed fact that all cycles seem to close (when coming back towards positive value of field) near \( H = 0 \), we define \( K \) experimentally by

\[ K = \frac{1}{4} \sigma_r H_r. \]

From the linear increase of \( H_r \) with Au concentration we can define the specific anisotropy energy per unit of Au concentration for CuMn\(_{1\%}\); we find:

\[ \frac{\Delta K_A}{\Delta x} [\text{Au}] = (3.5 \pm 0.5) \times 10^4 \text{ ergs/cm}^3 \text{ for CuMn}_{1\%}. \]

The displacement field at the centre of the hysteresis loop being approximately \( 1/2 H_r \) the corresponding elastic energy is found to be

\[ \frac{\Delta K_E}{\Delta x} [\text{Au}] = (1.75 \pm 0.5) \times 10^4 \text{ ergs/cm}^3 \text{ for CuMn}_{1\%}. \]

where the increased relative error allows for the fact that the centre of the cycle is often ill defined.

We remark as a conclusion of this analysis that in order to be able to define a specific anisotropy energy for an impurity as is done above we implicitly suppose that the anisotropy fields present in the CuMn\(_{1\%}\) are simply additive so that:

\[ K \text{ (alloy)} = K \text{ (CuMn)} + K \text{ (Au)} \]

with obvious notations. Such a simple relation will have to be present in any theoretical model dealing with this situation. The effect of other impurities (Al, Ag, Pt), although less documented than our Au measurements, again allows us to define an anisotropy field and an anisotropy energy using the same criterion as discussed for Au. The ensemble of our results appears in table II where we have calculated the anisotropy energy increment per \( \% \) added impurity in CuMn\(_{1\%}\), measured at 1.45 K, together with the hysteresis cycle width increment also per \( \% \) added impurity in CuMn\(_{1\%}\) at 1.45 K. The last line is the conduction electron spin flip scattering cross section measured from the spin resonance width increment studies of Cu containing these impurities. A special attention should be given in table II to the presence of Mn as an added impurity in CuMn\(_{1\%}\). The reason is that we believe that the residual anisotropy measured in CuMn has its origin in the properties of the Mn ion itself. However as it was shown [2] that the scaling of the elastic energy \( K_D \), and probably \( K_A \) as well, varies as the square of the Mn concentration, care should be exercised with the use of this number presented here for CuMn\(_{1\%}\). This procedure enables one to compare the residual anisotropy in different Mn alloys. The results for AgMn\(_{1\%}\) and PdMn\(_{1.3\%}\) (measured by Guy et al. [5]) are presented on table III.

It is striking to note that the order of magnitude of \( K_A \) is the same (within a factor of 2) for CuMn and AgMn.

The main conclusions to be drawn from table II concern the physical origin of the anisotropy in CuMn. As was shown as early as 1957 by Owen, Browne, Arp and Kip [15] from E.S.R. measurements.

**Table II.**

<table>
<thead>
<tr>
<th></th>
<th>Mn (*)</th>
<th>Ag</th>
<th>Al</th>
<th>Cu</th>
<th>Au</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta H_r/\Delta x \text{ Oe/%} ) (*)</td>
<td>170</td>
<td>&lt; 60</td>
<td>117 ± 10</td>
<td>6200 ± 400</td>
<td>34000 ± 13000</td>
<td></td>
</tr>
<tr>
<td>( \Delta K/\Delta x \text{ erg/mole Cu} ) (*)</td>
<td>70</td>
<td>&lt; 44</td>
<td>60 ± 6</td>
<td>2760 ± 400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta Z/t) ) (*)</td>
<td>4</td>
<td>0</td>
<td>+ 2</td>
<td>0</td>
<td>11000 ± 40000</td>
<td></td>
</tr>
<tr>
<td>( \Delta \sigma/\Delta (\text{Ae/%}) ) (*)</td>
<td>3.6 \times 10^{-3}</td>
<td>5.6 \times 10^{-3}</td>
<td>2.6 \times 10^{-3}</td>
<td>5.6 \times 10^{-3}</td>
<td>3.6 \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{se} \text{ (cm}^2\text{)} ) (*)</td>
<td>1.07 \times 10^{-18}</td>
<td>&lt; 10^{-18}</td>
<td>5.5 \times 10^{-19}</td>
<td>(1.2 ± 0.3) \times 10^{-17}</td>
<td>(4 ± 1) \times 10^{-17}</td>
<td></td>
</tr>
</tbody>
</table>

(*) Specific reversal field increment \( \Delta H_r/\Delta x \text{ per \% added impurity in CuMn}_{1\%}, \) measured at 1.45 K.

(\( \Delta K/\Delta x \text{ per \% added impurity in CuMn}_{1\%}. \)

(\( \Delta Z \)) Impurity valence difference with Cu.

(\( \Delta \sigma_{se} \)) Lattice parameter increment \( \Delta a/\Delta x \) from Ref. [16].

(\( \sigma_{se} \)) Conduction electron spin flip cross section for these different impurities.

(*) Mn is presented assuming Mn in CuMn\(_{1\%}\) is involved through its own spin orbit potential.
Table III. — Comparison of the anisotropy energies per mole of alloys for 3 systems: CuMn₁⁺%, AgMn₁⁺% (our work), and PdMn (Ref. [5]).

<table>
<thead>
<tr>
<th></th>
<th>CuMn₁⁺%</th>
<th>AgMn₁⁺%</th>
<th>PdMn₁⁻⁻⁻⁻%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K = \frac{1}{4}\sigma_s H_r$ (erg/mole alloy)</td>
<td>70 ± 7</td>
<td>147 ± 13</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>Measurement temperature</td>
<td>1.45 K</td>
<td>1.6 K</td>
<td>4.2 K</td>
</tr>
</tbody>
</table>

A comparison of the anisotropy energies per mole of alloys for three systems: CuMn₁⁺%, AgMn₁⁺% (our work), and PdMn (Ref. [5]).

The incremental anisotropy energy $\Delta K$ versus the conduction electron spin flip cross section $\Delta X(\%)$ for Ag, Al, Mn, Au, and Pt. $\Delta K = \frac{1}{4}\sigma_s H_r$ for CuMn₁⁺%, $\sigma_s$ is the conduction electron spin flip cross section for these different impurities in Cu [17, 18, 19]. Mn is presented assuming Mn in CuMn₁⁺% is involved through its own spin orbit potential.

Fig. 8. — Incremental anisotropy energy versus conduction electron spin flip cross section for Ag, Al, Mn, Au, and Pt.

The incremental anisotropy energy $\Delta K$ versus the conduction electron spin flip cross section $\Delta X(\%)$ for Ag, Al, Mn, Au, and Pt. $\Delta K = \frac{1}{4}\sigma_s H_r$ for CuMn₁⁺%, $\sigma_s$ is the conduction electron spin flip cross section for these different impurities in Cu. Mn is presented assuming Mn in CuMn₁⁺% is involved through its own spin orbit potential.
pretation of this shift [25] as being due to the anisotropy field of the alloy rather than an antiferromagnetic resonance as originally proposed by Owen et al. [15]. The consequence of this is that the incremental shift of the spin resonance by an added impurity in the spin glass can serve as a direct measure of the anisotropy. The quantitative comparison between these two methods is at present lacking but the order of magnitude agreement is very favourable.

As a conclusion we think that we have demonstrated the role of spin orbit scattering in determining the magnitude of the macroscopic anisotropy field in the spin glass phase. This fact offers a satisfactory explanation to the otherwise not understood difference in hysteresis behaviour of CuMn and AuFe (see Fig. 1). A natural question is to what extend this elementary mechanism is also operative in concentrated magnetic materials. Concerning the physics of the spin glass phase, the possible role of the anisotropy in determining the hysteresis behaviour of CuMn and AuFe (see Fig. 1).

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References

[9] As mentioned in [2], cold working a CuMn0.5% (from a diameter of 7 mm to a square 5 x 5 mm) don't change either the remanent magnetization or the reversible susceptibility within a few percents but broaden significantly the reversal field i.e. the field where occurs the first partial magnetization reversal.
[10] As it is well known [3, 7, 11], the value of the remanent magnetization is a function of the magnetic and thermal history; it depends for example on the speed which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed.
[11] As it is well known [3, 7, 11], the value of the remanent magnetization is a function of the magnetic and thermal history; it depends for example on the speed which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed. Our experimental technique introduces some inconvenients which at the field is removed.