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Domains and anisotropy in the amorphous ferro-spin glass (Fe$_{78}$Mn$_{22}$)$_{75}$P$_{16}$B$_6$Al$_3$

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Résumé. — L’aimantation de l’alliage amorphe ferro-verre de spin (Fe$_{78}$Mn$_{22}$)$_{75}$P$_{16}$B$_6$Al$_3$ a été mesurée en fonction du champ (0-30 kOe), de la température (1,5-300 K) et après que l’échantillon ait été refroidi soit en champ nul, soit dans un champ appliqué différent de zéro.

Les propriétés magnétiques de l’état réentrant ($T \lesssim 35$ K) sont discutées dans le cadre d’un modèle introduit précédemment à propos des alliages cristallins AuFe et NiMn. Ce modèle suppose l’existence de domaines ferromagnétiques de tailles « macroscopiques » dans l’état ferro.

Pendant le refroidissement à travers la phase réentrant, chaque domaine se fige dans la direction qu’il avait dans la phase ferro par l’apparition d’un champ d’anisotropie ayant la même direction que le domaine.

Par ailleurs, les résultats suggèrent que toute diminution du degré d’ordre ferromagnétique lorsque l’on traverse la transition (ferro→verre de spin) devrait se voir dans l’aimantation mesurée pendant le refroidissement de l’échantillon. Quant à la chute de l’aimantation à la transition mesurée en cours d’échauffement et après refroidissement dans $H = 0$, elle est dominée par des effets de rotation de domaines et de coercivité.

Une comparaison détaillée entre Au$_{82}$Fe$_{18}$ cristallin et (Fe$_{78}$Mn$_{22}$)$_{75}$P$_{16}$B$_6$Al$_3$ amorphe montre que les propriétés magnétiques les plus caractéristiques des deux alliages sont très similaires dans tous les cas considérés.

Ceci suggère que celles-ci ont un caractère très général et ne sont pas dues à des inhomogénéités métallurgiques comme cela a été parfois affirmé à propos de AuFe.

Abstract. — We report magnetic measurements on amorphous (Fe$_{78}$Mn$_{22}$)$_{75}$P$_{16}$B$_6$Al$_3$ as a function of field (0-30 kOe), temperature (1.5-300 K) and after the sample had been cooled through the spin glass ferromagnetic transition either with or without an applied field.

The relationships $m$ vs. $H$ and $m$ vs. $T$ in the reentrant (R) phase are discussed in terms of a domain approach introduced previously in connection with crystalline Ni$_{78}$Mn$_{22}$ and Au$_{82}$Fe$_{18}$. This approach assumes the existence of a « macroscopic » domain structure in the ferromagnetic phase. When the sample is cooled through the SG-FM transition temperature ($T_f$) the domain structure is quenched in by the onset of strong anisotropy forces in the reentrant phase.

The data suggest that any decrease in the degree of ferromagnetic order, as the sample is cooled through the R-FM transition, should be reflected in the FC-magnetization curve rather than in the ZFC-curve (measured during warming). The familiar sharp drop in the ZFC-magnetization is associated principally with domain rotation and coercitivity effects.

Comparison between amorphous (Fe$_{78}$Mn$_{22}$)$_{75}$P$_{16}$B$_6$Al$_3$ and crystalline Au$_{82}$Fe$_{18}$ shows that the two systems behave very similarly in almost every respect, suggesting that the characteristic behaviour of gold-iron is quite general and not connected with metallurgical effects as have been often claimed.

1. Introduction.

Amorphous (Fe$_{100-x}$Mn$_x$)$_{75}$P$_{16}$B$_6$Al$_3$ system is among the most investigated alloys that undergo a paramagnetic ferromagnetic transition [1-4] at a temperature $T_c$ followed by a second transition to a reentrant phase at a lower temperature $T_f$. The reentrant state will also be referred to as a mixed state in this paper. As has been discussed earlier with reference to crystalline alloys [5a, 6] (AuFe and NiMn) the term « mixed » means that spin glass disorder and ferromagnetic order coexist everywhere in the sample on a microscopic scale. However we have to be careful that such a coexistence does not seem to hold near the multi-
critical point where spin glass like behaviour may become dominant compared to ferromagnetic one (below the critical temperature $T_f$). Here we report an extensive investigation of the ZFC-magnetization, the FC-magnetization and magnetic irreversibilities (magnetic cycle and thermoremanence) in the alloy $(Fe_{78}Mn_{22})_7P_{16}B_6Al_3$ in which the concentration of iron ($x = 80 \%$) is much higher than the critical concentration ($x \approx 40 \%$) for $(Fe_{100-x}Mn)_2P_{16}B_6Al_3$ system [4].

In particular much attention is paid to the $m$ vs. $(H, T)$ relationship near and below the freezing temperature $T_f$. It is hoped that this will help to clarify the nature of this freezing which is currently the object of much discussion.

Obviously, a correct analysis of the magnetic data, particularly the familiar drop in the so-called non-equilibrium (or ZFC) magnetization ($m_{ne}$) from the demagnetization limited value $H/N$ is a necessary step, though not sufficient, for the understanding of the (R-FM transition).

The interpretation of the magnetic data, particularly the $m$ vs. $T$ curve below $T_f$, are still highly debated and there are, among experimentalists, at least three different points of view:

1. First, according to an approach introduced by us some time ago [5, 6], reentrant magnetism is characterized (I) by a "macroscopic" domain structure approximately the same as the domain pattern in the FM-phase just above $T_f$ and (II) by a gradual onset, during cooling, of strong unidirectional anisotropy fields that lock the domains to the lattice along their initial directions. We shall show that the present data are also consistent with this domain-anisotropy approach. Such an approach [5-7] has not received much attention in the literature and we want to concentrate on it in this article.

2. Secondly, a different picture [8, 9] (invoked mainly in connection with Au$_{100-x}$Fe$_x$) emphasizes the role of chemical inhomogeneities in the sample and ascribes the behaviour of the magnetization and other data as a function of $T$ and $H$ to individual plaquettes of few hundred atoms of nearly pure iron that have been seen in X-ray spectra of gold-iron system [10]. Since clustering in amorphous $(Fe_{78}Mn_{22})_7P_{16}B_6Al_3$ (if it exists) is probably different in size and structure from that in gold-iron system it seems fruitful to compare the present data with those of crystalline Au$_{82}Fe_{18}$ investigated previously [5c]. As will be seen in the course of this paper, the two systems exhibit very much the same behaviour, in almost every respect, leading to the conclusion that the magnetic properties seen in Au$_{100-x}$Fe$_x$ are undoubtedly not connected with metallurgical effects, but should have a more general character as claimed by Campbell et al. [11] and by Lauer and Kenne [12] (see also Refs. [13, 14, 15] for more details).

3. Finally, the sharp drop in $m_{ne}$ invoked previously have been often ascribed to the vanishing of the spontaneous magnetization in the reentrant phase [1-3]. More precisely, the temperature variation of the ZFC-magnetization (labelled $m_{ne}$ in this article) would be given by scaling laws with $m_{ne} \propto (T - T_f)^\beta$ for $H = 0$ and $T > T_f$ and $m_{ne} \propto H^{1/\delta}$ for $T = T_f$. Here, $\beta$ and $\delta$ are standard critical parameters.

Obviously the above pictures are contradictory, in particular no domain effects are allowed in the last two cases. The following remark and comments could provide some insights on the possible causes of these contradictions and would give more support to the domain-anisotropy picture [5] considered here.

Our remark is that, except in few cases [16], most of the theoretical works on ferro-spin glasses have been based on isotropic [17, 18] (Heisenberg or Ising) exchange Hamiltonians so that dipolar and anisotropic interactions are not taken into account in these theories [19]. However, there seems to be no reasons to neglect the roles of such energy terms in real alloys (and thus in actual experiments) where they should give rise to some kind of domains and magnetic anisotropy, respectively. We expect this to be especially true when the degree of ferromagnetic-order becomes significant, i.e. $\langle j_0 \rangle \gg 1$ where $\langle j_0 \rangle$ and $\langle j \rangle$ are the conventional mean values of the random (isotropic) exchange energy and its standard deviation from $\langle j \rangle$, respectively.

It is then tempting to suggest (by analogy with ordinary ferromagnets) that the sizes and the spatial distribution of the domains in the ferromagnetic phase ($T > T_f$) are imposed by the familiar interplay between dipolar and mean exchange energies (as well as magnetocrystalline energy in crystalline alloys). On the other hand, according to earlier transport and magnetic data [5a, 6] a spin disorder term (which is connected with $j$) would coexist with the spontaneous magnetization on a microscopic scale inside each domain. It is to be stressed too that coexistence of SG and FM orders is also necessary in order to get the magnetic anisotropy mentioned before.

As a matter of fact, if the anisotropy is induced by Dzyaloshinskii-Moriya like interactions, it is then possible to use (at least formally) Fert-Levy calculations [20] and get a triad anisotropy of the form $K \propto \sum_{ij} (S_i \times S_j) \cdot D_{ij}$ where $D_{ij}$ is a lattice vector of the sites $(i, j)$. In pure spin glasses, $K$ is invariant upon any rigid rotation of the whole system of spins with respect to the lattice vectors $D_{ij}$ so that a pure spin glass alloy is magnetically isotropic. This situation cannot hold for disordered ferromagnets because the existence of a spontaneous magnetization leads to a distribution of the spin vectors $S_i \times S_j$ which is no longer isotropic i.e. which is not invariant with respect to a rigid rotation of the spins relative to the lattice and consequently to an anisotropy even in the ZFC state.

A more intuitive way to see how macroscopic anisotropy could set in upon cooling below the R-FM
transition is to recall that the state of a disordered ferromagnet is thought to be equivalent to the state of a spin glass in an external field. The spontaneous magnetization playing the role of an isothermal remanent magnetization whereas the analogous of the external field is the average Weiss field

$$H_w = \frac{1}{\Lambda} \sum_{i=x,y,z}^N \langle S_i \rangle$$

where $\langle S_i \rangle$ is the average spin vector in the domain considered. Then, by analogy with pure spin glasses we expect that $H_w$ will behave like an effective cooling field leading to the manifestation of a macroscopic anisotropy field having roughly the same distribution as the domains themselves.

2. Experimental.

The amorphous $(Fe_{78}Mn_{22})_{75}P_{16}B_{6}Al_{3}$ investigated in this article was obtained by the melt spinning technique at the CECM-CNRS Vitry [21].

To minimize the effect of the demagnetizing field we used a small strip of about 2 mm width, 6 mm length and 35 μm thickness (~ 2.5 mg weight). The magnetization was measured with a home made vibrating sample magnetometer the sensitivity of which was about $10^{-9}$ emu and the field was defined to within 10 Oe for the low-$H$ measurements. The frequency of vibration was equal to 22 Hz and was provided by the internal oscillator of a PAR 124 Phase detector which constituted the central part of the whole set-up. To minimize the time effects, which are not the object of this study, we have taken care to make all the measurements as a function of $T$ in the same conditions (at the same time interval) about one minute after the temperature had been rapidly stabilized to the desired value. The low-$H$ magnetic cycle were also recorded in the same conditions and at the same sweep rate of the field (~ 1 kOe/min). We emphasize that the steepest parts of the $m$ vs. $H$ and $m$ vs. $T$ curves generally depend on the measuring time. Nevertheless the effects are small on the time scale of the experiments and do not change the qualitative shapes of the curves. Finally, to avoid any spurious time effects from the set-up itself we had set the time constants for the various apparatus to 10 ms.

3. Results.

3.1 Isothermal Magnetization.

3.1.1. ZFC Magnetic Cycle. — Figure 1 shows a series of magnetic hysteresis loops ($m$ vs. $H$) for $(Fe_{78}Mn_{22})_{75}P_{16}B_{6}Al_{3}$ cooled in zero field (ZFC) to different temperatures covering the reentrant phase.

Each loop was recorded immediately after ZF-cooling to the corresponding temperature, starting from $H = 0$ and following the sequence of arrows.

To begin, we consider the 1.8 K isotherm that exhibits the most characteristic spin glass like effects. Its principal feature concerns the initial magnetization section (dashed line) which varies very slowly and linearly with $H$ (passing underneath the cyclic loop) up to a critical field $H^* (1.8 \text{ K}) = 250 \text{ Oe}$. It then exhibits a sharp upturn at this field and finally tends rapidly towards technical saturation. This sort of behaviour is unusual in ordinary ferromagnets but has been observed in other reentrant amorphous systems [22] as well as in crystalline Au$_{81}$Fe$_{19}$ [5c].

As for the latter alloy, this can be associated with the macroscopic anisotropy fields discussed in the previous section. The magnitude of the anisotropy

![Fig. 1. — A set of hysteresis loops for amorphous $(Fe_{78}Mn_{22})_{75}P_{16}B_{6}Al_{3}$ plotted after cooling in $H = 0$ (ZFC) to the temperatures indicated in the figure. Note the position of the initial magnetization curve which (for $T = 1.8 \text{ K}$) intersects the cyclic loop and then presents a sharp knee at $H^* \approx 250 \text{ Oe}$.](image-url)
field would be approximately equal to the critical field $H^* = 250 \text{ Oe}$ [23]. It is this field that would hinder the rotation of the magnetic domains until the applied field becomes comparable to $H_c$.

A further interesting feature of figure 1 concerns the temperature variation of the width and the area of the magnetic loops. As can be seen the width is very large at the lowest temperatures (1.8 K isotherm) but drops rather abruptly upon warming and becomes indistinguishable from our lowest detectable field at 60 K (see inset of Fig. 1 which shows the low-$H$ behaviour in more details). This effect is best illustrated in figure 2 where we show the variation of the coercive field ($H_c$) together with the magnetic energy losses ($W$). From figure 2 we observe that these two quantities behave very similarly as a function of $T$: they are both large at the lowest temperatures and then fall-off rapidly in a temperature range extending roughly to 10 K. As in the case of Au$_{79}$Fe$_{19}$ (Figs. 1, 2, Ref. [5c]) we suggest that such a temperature region corresponds to the onset of a regime of strong irreversibilities associated with freezing of the longitudinal magnetization. Moreover, for $T$ higher than about 12 K we observe a considerable slowing-down in the energy losses which would be associated with a regime of low irreversibilities corresponding to the gradual freezing of the transverse magnetization. We insist that this sort of behaviour has been seen in gold iron system [5c], suggesting that the nature of freezing in the two alloys is the same.

3.1.2. FC magnetic cycle. — So far we have tried to single out some characteristic properties of the ZFC ($m$-$H$) graphs in the reentrant state of $(\text{Fe}_{78}\text{Mn}_{22})_{75}\text{P}_{16}\text{B}_{6}\text{Al}_{3}$. We now want to examine briefly the FC loop illustrated in figure 3 which offers some interesting features as well. The curves shown in figure 3 were recorded immediately after the cooling field ($H_c = 25 \text{ kOe}$) had been removed at 1.8 K. First of all, we note that the FC branch (labelled 25 kOe) is substantially shifted with respect to the ZFC one represented by the full loop on the same figure. However, as illustrated by the sequence of arrows, the shifted loop is totally irreproducible in the sense that if the field is further cycled (few times) between about $\pm 1 \text{ kOe}$ we never pass again by the shifted path (quoted 25 kOe) but instead we end up with a different loop which is very close to the ZFC loop shown previously in figure 1 for $T = 1.8 \text{ K}$. In addition, we observe that the reversal of the magnetization is accompanied by the onset of large time effects. These irreversibility effects are probably connected with a non-rigid reversal of $m$ [23] as in the AuFe system (Fig. 3 of Ref. [5c]).

Interestingly enough, we observe that the reversal field $H_r$, $H_r \approx 270 \text{ Oe}$ corresponding to $m = 0$ on the shifted cycle (Fig. 3) is approximately equal to $H^*$ (1.8 K) ($\sim 250 \text{ Oe}$) marking the knee in the initial magnetization curve displayed in figure 1 for $T = 1.8 \text{ K}$. The equality between the two fields is probably not fortuitous and suggests that they probably have the same origin and would both correspond to the same anisotropic exchange interaction. This is in agreement with the idea already discussed in the previous section that the magnitude of the anisotropy field should be

![Fig. 2. — Temperature variation of the magnetic energy losses (— — —) together with the coercive field (——) for $(\text{Fe}_{78}\text{Mn}_{22})_{75}\text{P}_{16}\text{B}_{6}\text{Al}_{3}$ cooled in $H = 0$.](image)
roughly independent of the domain pattern and therefore of the cooling-field. Finally, we again remark how similar are the behaviours of Au$_{82}$Fe$_{18}$ and (Fe$_{78}$Mn$_{22}$)$_{75}$P$_{16}$B$_{6}$Al$_{3}$ by comparing the magneto-thermal effects shown in figure 3a of reference [5c] and in figure 3 of the present paper.

3.1.3 High field magnetization. — We now focus on the field variation of the magnetization in relatively high fields (0-30 kOe) and for a selected set of temperatures going from 1.5 to 276 K. Considering the isotherms displayed in figure 4, it is seen that after an initial and very rapid growth, due to the rotation of the ferromagnetic domains, the magnetization does not actually saturate but continues to increase slowly but steadily up to our highest available field. At the lowest temperatures where low-energy magnetic excitations are frozen, this reflects the persistence of a large amount of spin disorder after the « spontaneous » magnetization had been lined up by an applied field of few hundred Oe. Such a high field behaviour is typical of mixed spin glass ferromagnetic alloys, particularly Au$_{82}$Fe$_{18}$ [21]. It is to be stressed however that the change in the magnetization ($m$ (30 kOe) - $m$ (5 kOe) $\approx$ 5 emu at 1.5 K) after the complete rotation of the domains, is extremely small compared to the increase in $m$ ($\sim$ 80 emu) due to this rotation. As in the gold-iron system [24] this reflects the persistence of a high degree of spin glass-like disorder after the spontaneous magnetization had been lined up by the applied field.

3.1.4 Paramagnetic-ferromagnetic transition. — In order to characterize more fully the magnetic properties of our sample we have also performed a detailed investigation of the $m$ vs. $H$ relationship near the Curie-point $T_c$. This is illustrated in figure 5 by a series of Arrott plots in the form $m^2$ vs. $H/m$. Interestingly enough, the Curie point ($T_c$ = 267 ± 1 K) is found to be extremely well defined suggesting that the present alloy is relatively homogeneous magnetically as well as metallurgically, even though the slight deviation from linearity for low $H/m$ values (Fig. 5) could be the signature of some small inhomogeneities according to the Rhodes-Wohlfarth analysis [25]. On the other hand the value $T_c$ = 267 K found here is close to, but somewhat lower than, that ($T_c$ = 280 K) deduced from reference [1].

3.2 Isofield magnetization.

3.2.1 Equilibrium and non-equilibrium magnetizations. — Figure 6 gives the variation of the magnetization as a function of temperature for several fixed fields and after the sample had been prepared in three different magnetic states. We begin with the ZFC curve to which we have already referred as the non-equilibrium magnetization ($m_{ne}$). An important feature of the $m_{ne}$ curves shown in figure 6 is that, below a certain threshold temperature $T^*(H)$, it stays very low and nearly independent of $T$. The examination of this section of the curve reveals that it is fairly reversible upon successive cooling-heating operations with no significant time effects on the time scale of the experiment ($\sim$ 10 min). However, for higher $T$ ($T > T^*(H)$) $m_{ne}$ rises rather abruptly in a narrow temperature range ($8 \leq T \leq 15$ K) and then levels-off gradually tending towards the value $H/N$ (attained at $T \sim 35$ K for $H = 15$ Oe) imposed by the reciprocal demagnetization factor $N$. The steepest part of the...
Fig. 6. — Magnetization vs. temperature for three different fields (15, 30 and 60 Oe). Curves labelled ZFC, traced after cooling in $H = 0$ to 1.5 K and then heating in the indicated fields. These curves are called $m_{\text{ZFC}}$ in the text. Dashed lines, referred to as $m_{\text{eq}}$ in the text, traced during cooling in the indicated fields. The curves labelled $m_r$ correspond to the thermo-remanent magnetization measured during cooling, after the removal of the cooling fields. Note the symmetry between $m_r$ and $m_{\text{eq}}$ ($m_r + m_{\text{eq}} - m_{\text{ZFC}}$).

4. Discussion.

4.1 Equilibrium magnetization curve. — It was seen in the previous section that the equilibrium magnetization $m_{\text{eq}}(T)$ (dashed line Fig. 6) was essentially independent of temperature. We would like to stress, using simple magnetostatic arguments, that such a property ($m_{\text{eq}}(T) = \text{constant}$) has some important consequences for the structure of the magnetization in the mixed phase. To see this we recall that in the ferromagnetic region the internal field, $H_{\text{int}}$, is equal to zero (low fields):

$$H_{\text{int}} = H - N m_{\text{eq}} = 0.$$  

Since the three terms ($H$, $N$ and $m_{\text{eq}}$) in the right hand side of equation (2) remain constant during cooling, it follows that the effective cooling field ($H_{\text{int}}$) is actually equal to zero. Therefore, even though the applied field is different from zero, the equilibrium curve ($m_{\text{eq}}$) corresponds in fact not to FC but to ZFC conditions as long as equation (2) is obeyed. Obviously this should imply that the structure of the magnetization does not change significantly during these ZFC conditions, particularly in the limit $H \to 0$. In other terms, the domain pattern in ferro-spin glass alloys should be essentially the same in the reentrant phase and in the ferromagnetic phase near $T_f$. This conclusion is in accordance with previous conclusions drawn (for Ni$_{79}$Mn$_{21}$ and Au$_{82}$Fe$_{18}$ alloys) from different arguments and different experiments [5, 6].

However, we have to be careful because in many other alloys considered as ferro-spin glasses, $m_{\text{eq}}$ exhibits a more or less marked drop near and below $T_f$ so that equation (2) ceases to be true in these cases. In general the drop in $m_{\text{eq}}$ becomes more and more important when the composition approaches the multi-critical point separating the « spin glass » and the ferromagnetic phases suggesting that such a fall-off in the FC-magnetization is a pure spin glass effect. Moreover, the anisotropy fields discussed previously must have the direction of the FC magnetization (i.e. of $m_{\text{eq}}$) and cannot be invoked to explain the variation of $m_{\text{eq}}$. It seems therefore that the only reasonable explanation for the decrease in $m_{\text{eq}}$ is a diminution in the long range ferromagnetic order and as a possible consequence modification of the domain structure during cooling.

4.2 Non-equilibrium magnetization curve. — We now wish to discuss qualitatively how a domain-anisotropy picture could explain some of the present experimental results, particularly the correlation between $m_r(T)$, $m_{\text{eq}}(T)$ and $m_{\text{eq}}(T) = H/N$ given by formulae (2). We have already noted that as long as...
the internal field is smaller than the anisotropy field \( (H_{\text{int}} < H_s(T)) \) the magnetic domains will remain firmly anchored to the lattice and the ZFC-magnetization will therefore stay very low \( (m_{\text{ne}}(T) \sim 0) \) in qualitative agreement with the temperature variation of the curves in figure 6 for \( T < T^* \). However, when the limit \( H_{\text{int}} = H_s(T) \) is reached by varying either \( H \) or \( T \) the magnetization \( m_{\text{ne}} \) will no longer be locked to the lattice and will rotate away from its initial direction in such a way as to maintain the balance \( H_s = H_{\text{int}} = H - Nm_{\text{ne}}(T) \) between the anisotropy field and the internal field. From the above qualitative arguments (within the present domain picture) it follows that \( m_{\text{ne}}(T) \) would be given by:

\[
\begin{align*}
m_{\text{ne}} & \sim 0, \quad H \leq H_s(T) \\
m_{\text{ne}} & \sim \frac{H - H_s(T)}{N}, \quad H \geq H_s(T).
\end{align*}
\]

This is not inconsistent with the variation of \( m_{\text{ne}} \) with \( T \) shown in figure 6 if we identify \( H_s(T) \) with the field \( H^*(T) \) indicated in the figure (we recall that as in spin glasses, \( H_s(T) \) is expected to decrease monotonously with \( T \) becoming equal to zero at \( T_f \)).

We can also explain the variation of the thermoremanent magnetization \( m_r(T) \) with \( T \) (Fig. 6) in the same way except that in this case the internal field is negative whereas the applied field is equal to zero. For this, we first check that at the lowest temperatures the magnitude \( (Nm_r < 60 \text{ Oe}) \) of the internal field associated with any of the curves in figure 6, is smaller than the anisotropy field \( H_s(H_s \sim 250 \text{ Oe}) \). Then, as long as the condition \( Nm_r < H_s(T) \) is verified (i.e. as long as the anisotropy field is higher than the demagnetizing field) we expect that \( m_r(T) \) will stay locked to the lattice and will not vary significantly with \( T \) (i.e. \( m_r(T) \sim H/N \)). This situation would hold until \( H_s(T) \) becomes equal to \( Nm_r(T) \approx H \). After that, if \( T \) is further increased \( m_r(T) \) will rotate away from its initial direction in order to maintain the equilibrium condition \( H_{\text{int}} + H_s(T) = 0 \).

It, thus, follows that \( m_r(T) \) would be given by:

\[
\begin{align*}
m_r & \sim H/N, \quad H < H_s(T) \\
m_r & \sim \frac{H_s}{N}, \quad H > H_s(T).
\end{align*}
\]

adding equations (3, 4) and (5, 6) term by term yields the experimental result \( m_{\text{ne}} + m_r = m_{\text{eq}} \) of formula (2).

5. Conclusion.

In conclusion we have extended the study of the magnetic properties of amorphous \((\text{Fe}_{78}\text{Mn}_{22})_{75}\text{P}_{16}\text{B}_{6}\text{Al}_{3}\) to a wider range of field and temperature. In particular, for the first time, to our knowledge, a systematic investigation of the magnetic irreversibilities (both as a function of \( H \) and \( T \)) in this alloy are reported and compared with irreversibilities in the highly debated system crystalline gold-iron.

An important distinction is established between the ZFC-magnetization \( m_{\text{ne}} \) (measured during heating) and the FC-magnetization \( m_{\text{eq}} \) (measured during cooling) in the sense that \( m_{\text{ne}} \) is thought to be controlled essentially by domains and coercitivity effects whereas \( m_{\text{eq}} \) is mainly sensitive to changes in the degree of ferromagnetic order inside the domains themselves. In another way this means that as for the ferromagnetic-paramagnetic transition, the study of the R-FM transition can be obscured by domain and coercitivity effects which have to be taken into account in this case too before comparison is made with theoretical predictions.

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References

[19] An interesting phenomenological description proposed by Souletie (SOULETIE, J., J. Physique 44 (1983) 1095) seems to be able to account for some of the domain and coercitivity behaviours in ferro-spin glasses.
[23] As will be reported elsewhere, the reversal of the magnetization at $H^*$ seems not to be rigid so that $H^*$ is probably smaller than the anisotropy field that could be measured in the limit of very small deviation of $m$ from its equilibrium direction, in the presence of a weak transverse field for instance.