Ageing phenomena in a spin-glass: effect of temperature changes below Tg

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Ageing phenomena in a spin-glass : effect of temperature changes below T_g

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Résumé.- Les propriétés magnétiques d'un verre de spin dépendent du temps passé dans sa phase basse température : c'est le phénomène de vieillissement. Nous présentons des mesures de susceptibilité alternative à basse fréquence (0.01 à 0.1 Hz) et de relaxation de l'aimantation thermo-rémanente dans le verre de spin isolant $CdCr_{1.7}In_{0.3}S_4$; nous étudions l'influence de variations de température sur le vieillissement dans la phase verre de spin pour mieux interpreter le mécanisme de ce processus. Le large spectre de temps de relaxation observé dans la dynamique des verres de spins reflète l'existence de nombreuses vallées d'énergie dans l'espace des phases ; une organisation hierarchique de ces vallées, dont les bifurcations apparaissent quand la température diminue, est le schéma le plus simple qui prenne en compte l'ensemble de nos résultats.

Abstract.- The magnetic properties of a spin-glass depend on the time spent in the low-temperature phase : this is the so-called ageing phenomenon. We present measurements of the low-frequency a.c. susceptibility (0.01 to 0.1 Hz) and of the relaxation of the thermo-remanent magnetization in the $CdCr_{1.7}In_{0.3}S_4$ insulating spin-glass ; we investigate the influence of temperature variations on the ageing processes in the spin-glass phase, in order to get a better insight into their mechanism. The wide spectrum of relaxation times observed in spin-glass dynamics reflects the existence of many energy valleys in the phase space ; a hierarchical organization of these valleys, whose bifurcations appear as the temperature is decreased, is the simplest picture which accounts for our results.

1. Introduction.

The dynamics of a spin-glass quenched into its low temperature phase is characterized by a history-dependent behaviour. Although its field-cooled magnetization varies only very slightly with time, the spin-glass state continues to evolve ; it has been shown for several different compounds that the decrease of the thermo-remanent magnetization (T.R.M.), after the field cut-off, strongly depends on the "age" t_a of the system, i.e. the time elapsed since it was quenched [1 to 6]. In a T.R.M. measurement, the field is turned off at a time t_w (waiting time) after quenching, and the decrease of the remanent magnetization is recorded as a function of the observation time t counted from the field cut-off. Starting from an analysis first introduced in the study of the mechanical properties of glassy polymers [7], we have proposed a global phenomenological description of the T.R.M. relaxation [3 to 6]. We have shown that two different contributions to the relaxation can be distinguished :

— a stationary part, predominant at short times when compared to the waiting time ($t_w \gg t$)

— a non-stationary part (i.e. age dependent) which increases the relaxation rate when the observation time becomes of the order of the waiting time.

Actually, on the experimental time scale (a few seconds to a few days), these two contributions are mingled ; a very accurate description of the stationary part cannot be drawn from the T.R.M. relaxation alone, since the time range explored corresponds mainly to the non-stationary regime.

In contrast to T.R.M. experiments, a.c. susceptibility measurements offer the opportunity to fix the observation time, which remains equal to the inverse of the excitation frequency ν, and to observe the response as a function of the age t_a of the system ; a.c. susceptibility is a priviledged tool to explore the stationary dynamics ($t_a >> 1/\nu$) of the spin-glass phase. However, if ν is low enough to allow an experiment at $t_a \sim 1/\nu$, it also gives access to ageing phenomena ; Lundgren *et al.* [8] have already evidenced a time dependence of the out-of-phase susceptibility χ'' in CuMn during several minutes after a temperature step, at a frequency ν=1.7Hz. Our lower frequency range (0.01-0.1 Hz) allows us to observe ageing effects on both components of the a.c. susceptibility during at least several hours.

We have performed measurements of both T.R.M. relaxation and a.c. susceptibility, on a time scale which concerns mainly the non-stationary part of the dynamics ; we concentrate on the influence of temperature variations below T_g. The existence in the spin-glass phase of relaxation times with no apparent upper bound indicates that, in a given time window, only a part of the total phase space can be sampled ; indeed, as frustration generates numerous energy valleys in the phase space, the quenched system can be trapped in some regions for macroscopic times. Ageing phenomena can be described as a slow evolution towards the equilibrium probability distribution among the different valleys. The existence of an age independent relaxation for $t_a >> t$ favours a strong similarity between the local properties of these valleys. We study here how temperature affects the structure of the valleys and the equilibration of the spin-glass among them. We restrict ourselves to an experimental test of some general hypotheses which can be used to describe spin-glass dynamics ; although this work already sets some quantitative limits to the compared influences of time and temperature, the precise definition of their relationship would form the subject of a series of specifically focused experiments, and is not our present purpose.

We describe the experimental procedure in section 2. Section 3 is devoted to the effect of crossing T_g ; we show that ageing does not simply stem from some delay due to fast cooling through T_g, but rather reflects an intrinsic property of the spin-glass phase. The concept of a single effective spin temperature, which would progressively equalize with that of the lattice, cannot account for our results ; ageing must be considered a more complex thermalization mechanism. In order to clarify this mechanism, we have studied the consequence on ageing of heating or cooling. Section 4 describes memory effects which affect the evolution of ageing when temperature is decreased, while section 5 shows that partial annealing can reinitialize the ageing processes at short times. These different observations favour a hierarchical description of the phase space organization.

2. Experimental procedure.

The measurements were done with a powder sample of the $CdCr_{1.7}In_{0.3}S_4$ insulating spin-glass.The critical behaviour of this compound near T_g = 16.7 K has been studied previously in a.c. [9] and d.c. [10] susceptibility measurements. The very low field (0.1 Oe) T.R.M. relaxation has been analysed in [6]. In the present work, the applied field is 20 Oe ; our analysis of the relaxation remains valid in this field range, as explained in [5] where the influence of the field magnitude is investigated. The recording procedure is the same as in [5] ; the detection of the magnetization by the classical amplification of the voltage induced while extracting the sample from the pick-up coils allows a reliable determination of the baseline signal.

The solid lines in figure 1 illustrate the dependence of the T.R.M. relaxation on the waiting time t_w before the field cut-off. The relaxation curves obtained for t_w = 15, 30 or 900 min are clearly different : they depend on the two time variables t and t_w. However, in such an experiment, when t elapses the age $t_a = t + t_w$ also increases ; as detailed in [4-6], the two "natural" variables (t_w,t) can be replaced by $(\lambda, \lambda/(t_w)^\mu)$, where λ is a fictitious time elapsing at constant age, defined as

$$d\lambda/(t_w)^\mu = dt/(t+t_w)^\mu ,$$

and μ is an exponent depending only on temperature in the range of fields and t_w values investigated. This representation allowed us to take full account of the t_w dependence of the relaxation curves ; when plotted as a function of the relevant time variables (λ, $\lambda/(t_w)^\mu$), they can all be superimposed on a unique master curve.

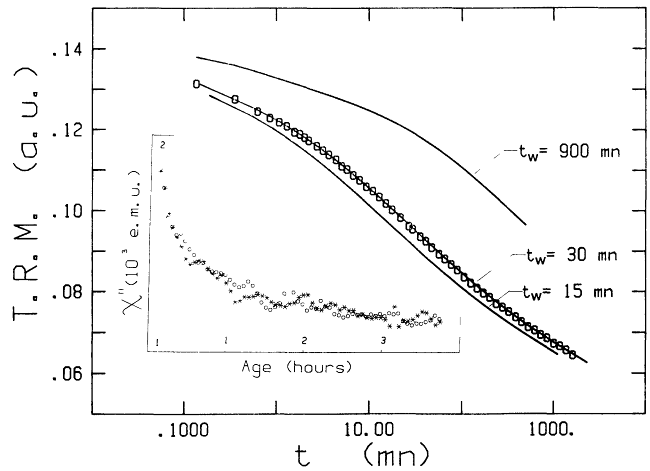

Fig. 1.-Influence of a 900 min waiting time at 0.96 T_g (16K) on ageing at 0.72 T_g (12K). The insert shows a 0.01 Hz χ'' measurement as a function of the time elapsed since the sample was cooled to 0.72 T_g, in hours. The stars (*) are obtained when the sample is directly quenched from above T_g, while the circles (O) correspond to the experiment with an intermediate waiting time at 0.96 T_g. The main part of the figure presents relaxations of the T.R.M., in arbitrary units, *versus* the time from the field cut-off, in minutes. The effect of the intermediate stay at 0.96 T_g (open circles) is displayed in the case of a t_w = 30 min experiment at 0.72 T_g ; the solid lines allow a comparison with standard t_w= 15, 30 or 900 min experiments.

Within the T.R.M. accuracy, we have proposed a mathematical description of the relaxation function σ which is a product of a power law and a stretched exponential :

$$\sigma \quad \alpha \quad \lambda^{-\alpha} \exp\left(-\left(\frac{\lambda}{\tau_p \cdot (t_w)^{\mu}}\right)^{1-n}\right).$$

In the limit $t << t_w$, the power law is predominant and $\lambda \sim t$; the fact that the relaxation is independent of t_w denotes a stationary process. If this limit can be extended to $t_w \rightarrow \infty$, the stationary dynamics represents the equilibrium response of the spin-glass.

Let us mention that, in the present paper, *the data analysis is independent of the choice of a functional form for the relaxation.*

The a.c. susceptibility results have been obtained with a SQUID magnetometer at very low frequency (0.01-0.1 Hz) and applied field (0.001 Oe), using a digital method described elsewhere [11]. Figure 2 presents the polar representation of the complex susceptibility measured at 0.01 Hz and 0.72 T_g, as a function of the time elapsed since the sample was cooled below T_g. The phase of the susceptibility, which corresponds to the ratio of the dissipated to the stored magnetic energy, is after 10 minutes still about 50% higher than its equilibrium value, while this excess is only 5% for its modulus. The main ageing effect for the a.c. susceptibility is thus the progressive decrease (as t_a elapses) of the excess dissipation observed at small age. In the insert, we have reported the results obtained for ν=0.1Hz ; the a.c. susceptibility approaches its equilibrium value in a time interval roughly proportional to $1/\nu$, in agreement with the definition of the reduced variable $\lambda/(t_w)^{\mu}$ ($\mu \sim 1$).

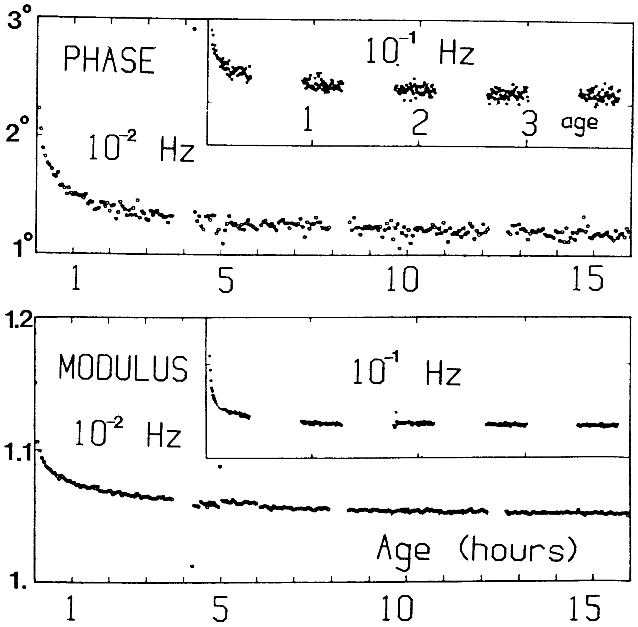

Fig. 2.-The phase and modulus of the a.c. susceptibility measured at 0.01 Hz (0.1 Hz in the inserts) and 0.72 T_g (12K), as a function of the age (time elapsed since the sample was quenched below T_g) in hours. The phase is expressed in angular degrees, and the modulus in arbitrary units.

3. Quenching below T_g and spin thermalization.

There are many experimental evidences for a very wide spectrum of relaxation times for the spin-glass, and its quite slow trend towards equilibrium is not astonishing. One can wonder if ageing phenomena might be explained by a delay of the expected divergence of the correlation length at T_g. A related effect has been observed by Beauvillain *et al.* [12], who find just above T_g a slight dependence of the field-cooled magnetization on the cooling rate. This dependence is found to occur when the cooling procedure is too rapid to match the long-time rearrangement processes in the spin-glass. In our present experiments, we have not found, within the experimental accuracy, any cooling rate dependence (nor even relaxation) of the field-cooled magnetization. However, in order to test the influence of T_g crossing on the appearance of ageing phenomena, we have performed an experiment in which the spin-glass is kept a long time just below T_g before completing the temperature decrease.

The sample is field-cooled from 1.5 T_g to 0.96 T_g, and kept 900 min at this temperature before measuring at 0.7 T_g. Both a.c. susceptibility and T.R.M. experiments give the same result : the relaxation of the T.R.M. after 30 min at 0.7 T_g (Fig. 1) and the age dependence of χ'' (insert in Fig. 1) are the same as if the spin-glass had been directly cooled from above T_g to the measurement temperature. Hence, ageing cannot be ascribed to a freezing of the growth of the correlation length due to a rapid crossing of the transition temperature : a very long time spent near T_g does not bring the system closer to its equilibrium state at a lower temperature. The behaviour appears very similar to that of the "chaotic" spin-glass phase described in [13,14]. In these papers, it is argued that spin correlations in the ordered phase should be a chaotic function of temperature ; within this context, even a configuration very close to equilibrium at a given temperature would be deeply affected by a temperature variation.

In a χ'' *versus* χ' plot (ν=0.04 Hz), figure 3 illustrates the evolution of the system after a temperature step. The full points represent the variation of the complex susceptibility when, after a waiting time of 24 hours at 0.84 T_g, the sample is rapidly cooled down to 0.72 T_g (less than 1 min). The evolution is compared to the series of quasi-equilibrium values (open circles) obtained after waiting 24 hours at different temperatures between 0.1 and 1.1 T_g. The comparison shows that the evolution of

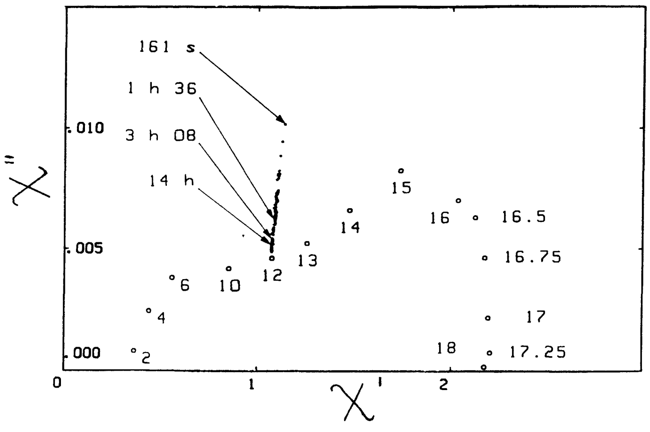

Fig. 3.-Quasi-equilibrium values (after 24 hours) of the a.c. susceptibility (open circles) measured at 0.04 Hz, in a χ'' *versus* χ' plot, for temperatures ranging from 0.1 to 1.1 T_g (2K to 18K). The arbitrary units are the same for χ' and χ''. The full points are transitory values obtained when, after a waiting time of 24 hours at 0.84 T_g (14K), the sample is cooled in less than 1 min to 0.72 T_g (12K). The time elapsed after the cooling is indicated.

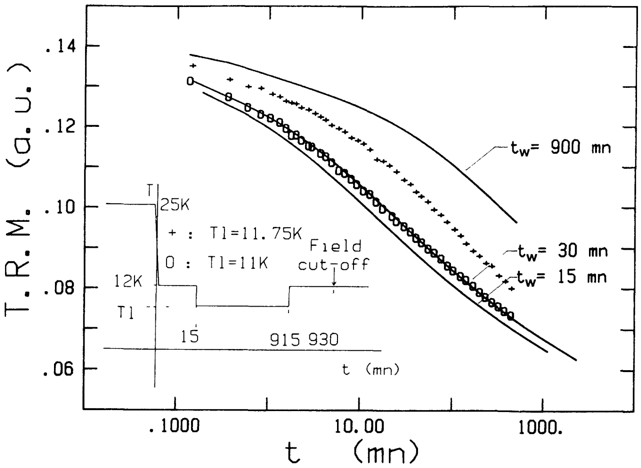

Fig.4.-Effect on ageing at 0.72 T_g (12K) of a 900 min waiting time at a lower temperature T_l. The temperature variation during the total waiting time is sketched in the insert. The solid lines are standard relaxation recordings for t_w = 15, 30 and 900 min. The T.R.M. is plotted in arbitrary units, as a function of the time from the field cut-off, in minutes. The open circles (O) are obtained for $T_l = 0.66\ T_g$ (11K), and the crosses (+) for $T_l = 0.70\ T_g$ (11.75K).

the ageing susceptibility cannot be represented by a succession of equilibrium points at other temperatures. Hence, the definition of a specific spin temperature, different from that of the lattice during the ageing process, appears to be irrelevant ; it would be unable to account for the variation of the complex susceptibility measured after a temperature step.

The latter experiment can be pursued further. If, after this period of 24 hours at 0.72 T_g, the sample is now heated back to 0.84 T_g, no ageing is observed : the a.c. susceptibility reaches its stationary value almost immediately. Hence, the quasi-equilibrium (on our time scale) which had been reached at 0.84 T_g before cooling has been preserved during the evolution at the lower temperature ; increase or decrease of the temperature appears to influence ageing in very different ways. We show in the following sections how a further study of the effect of temperature changes can yield a better understanding of the ageing mechanism.

4. Freezing of the ageing process : a memory behaviour.

We now turn to an experiment in which the temperature is temporarily decreased during ageing, in order to see how the spin-glass evolution is thereby affected. The procedure (which is sketched in the insert of fig. 4) is as follows : the sample is field-cooled and kept 15 min at 0.72 T_g, then cooled and kept at 0.66 T_g during 900 min. After this long time at 0.66 T_g, the sample is heated back to 0.72 T_g, and after 15 min the field is cut off and the T.R.M. is measured. Figure 4 displays the results ; in spite of the very long period at 0.66 T_g, a temperature at which ageing effects are easily observable [6], the relaxation obtained (open circles O) cannot be distinguished from that measured after a simple waiting time t_{w_0} = 30 min at 0.72 T_g, and is clearly different from that obtained for 15 min (solid lines). The time spent at 0.66 T_g is completely ineffective regarding the evolution at 0.72 T_g : when cooled down, the system becomes apparently frozen in its state at t_w = 15 min, and when re-heated, its evolution restarts from that state.

Actually, a slowing down of the relaxation is expected when the temperature is decreased. But, as far as the slowing down of the T.R.M. relaxation and that of ageing can be compared, the increase of the time constant τ_p defined in section 2 (50% from 0.72 to 0.66 T_g [6]) seems to be quite inadequate to describe this freezing effect. Such a combined influence of time and temperature has already been explored in studies of the CuMn magnetization relaxation in the vicinity of saturation (H=10kOe) [15,16]. In these references, the authors represent their data as a function of the unique reduced variable $T.\mathrm{Ln}(t/\tau_0)$, where $\tau_0 \sim 10^{-13}$s is a microscopic time. This prompts us to compare the real time t_{low} spent at 0.66 T_g with an equivalent effective time t_{high} at 0.72 T_g defined as :

$$0.72 \times \mathrm{Ln}\,(t_{\mathrm{high}}/\tau_0) = 0.66 \times \mathrm{Ln}\,(t_{\mathrm{low}}/\tau_0)\ ,$$

but for t_{low} = 900 min this relation yields $t_{\mathrm{high}} \sim 30$ min. Within this picture the relaxation observed should correspond to $t_w \sim t_{high} + t_{w_0} = 60$ min rather than to $t_w = t_{w_0} = 30$ min, in flagrant disagreement with our result ; in order to explain the apparent freezing of ageing at 0.72 T_g, i.e. to obtain $t_{high} << 30$ min, τ_0 must be given unphysical values as short as 10^{-20}s.

The comparison of ageing at 0.96 and 0.72 T_g (Section 3) suggests that, at least on experimental time scales, the evolutions of the spin-glass towards a more favourable energy configuration at such different temperatures follow from independent processes. In the present experiment, where the temperature is only decreased from 0.72 to 0.66 T_g, this behaviour is still observed. Moreover, the 0.72 T_g configuration is retrieved after a very long-time evolution at 0.66 T_g. This implies that the evolution at a lower temperature occurred among valleys in the phase space which are subdivisions of those at the higher temperature : a temperature decrease gives rise to a ramification of the phase space organization.

A 0.06 T_g step was enough to prevent the evolution at the lower temperature from affecting the higher temperature configuration in our time scale. Obviously, there must be a lower bound to the value of the temperature gap which yields this effect ; we have performed the same experiment with a step of only 0.015 T_g. The result is also shown in figure 4 (crosses +) : the measured relaxation is significantly different from that at t_w = 30 min.

5. Partial annealing and ageing reinitialization.

In section 4, a decrease of the temperature was seen to give rise to a memorization of the state reached during the higher temperature stages. We now describe the inverse experiment : what is the effect on ageing of a slight re-heating ?

Figure 5 shows a comparison between the a.c. susceptibilities measured at 0.04 Hz and 0.72 T_g in the following conditions :

i) The measurement begins right after quenching from above T_g (open circles O). We obtain the usual ageing behaviour.

ii) When the decrease of χ'' has become negligible as compared to the scale of the figure (after 3 hours), the sample is heated to 0.84 T_g during 5 min, and cooled back to 0.72 T_g. The ageing susceptibility (crosses +) is identical to that obtained after quenching from above T_g : ageing is reinitialized in the time window explored in this experiment, i.e. $t \sim 1/\nu = 25$ s and $t_a = 1$ to 150 min.

iii) Same procedure as ii), but heating only up to 0.73 T_g (stars *). Ageing has been practically unaffected by this small annealing.

In order to explore larger characteristic times, we have performed a T.R.M. measurement in analogous

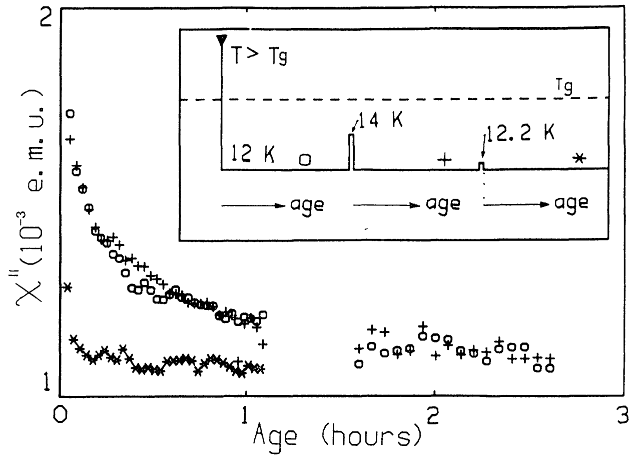

Fig. 5.-Effect on χ'' at 0.04 Hz and 0.72 T_g (12K) of a slight annealing. χ'' is plotted in 10^{-3} e.m.u. *versus* the time elapsed since the sample temperature reached 0.72 T_g. The procedure is sketched in the insert. The open circles (O) are obtained when the sample is directly quenched from above T_g. When the decrease of χ'' has become negligible, the sample is heated 5 min at 0.84 T_g (14K) ; χ'' measured after this short annealing is displayed in crosses (+). The same procedure, but at 0.73 T_g (12.2K) instead of 0.84 T_g, yields the stars (*).

conditions. The sample is field-cooled from 1.5 to 0.72 T_g and kept 900 min at this temperature ; then it is annealed to $T_a = 0.78$ or 0.84 T_g during only 5 min, and finally kept 30 min at 0.72 T_g before turning off the field and recording the T.R.M. relaxation. In figure 6, the relaxations obtained

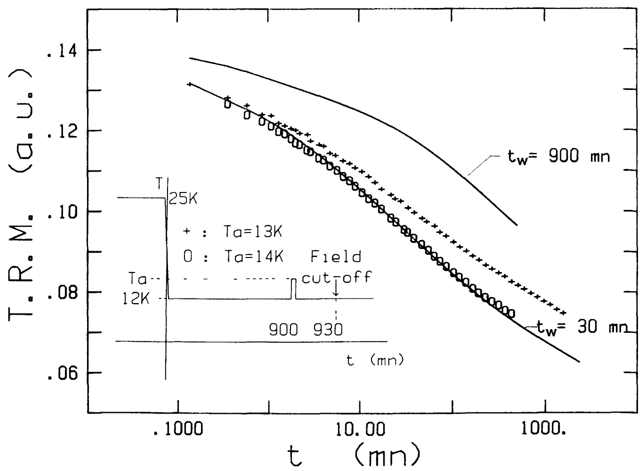

Fig. 6.-Effect on the T.R.M. relaxation at 0.72 T_g (12K) of a slight annealing. The T.R.M. is plotted in arbitrary units as a function of the time from the field cut-off, in minutes. The solid lines are standard measurements for t_w = 30 and 900 min. The open circles (O) ($T_a = 0.84$ T_g = 14K) and the crosses (+) ($T_a = 0.78$ T_g = 13K) are obtained when the sample is heated to T_a for 5 min after a 900 min waiting time at 0.72 T_g, and after another waiting time of 30 min at 0.72 T_g before the field is switched off ; the procedure is sketched in the insert.

(crosses + for $T_a = 0.78\ T_g$ and open circles O for $T_a = 0.84\ T_g$) are compared to that observed for $t_w = 30$ min after a direct quenching from 1.5 T_g (lower solid line). For short times, the three curves are merging ; this is in agreement with the χ'' result. But, as time elapses, the relaxation in the reheated state is slowed down. After annealing 5 min at 0.84 T_g, the effect of the 900 min previously spent at 0.72 T_g is almost completely erased, except in the long time part of the relaxation curve (open circles O), which is slightly slowed down : ageing has been reinitialized on the major part of the experimental time scale. In contrast, the relaxation obtained after annealing 5 min at 0.78 T_g (crosses +) only overlaps the standard relaxation curve for $t_w = 30$ min at its beginning : annealing at 0.78 T_g has only reinitialized the short time processes.

As in section 4, an organization of the phase space ramifying as the temperature is decreased is probably the most powerful picture to describe these results. Actually, a highly non-trivial non-ergodicity is predicted by mean-field theories of the spin-glass phase, due to the existence of an infinite number of valleys in the phase space [17] ; as a result, a hierarchical (and ultrametric) structure of these valleys is found [18], but the non-ergodicity is absolute : no transitions between valleys can occur. An *effective* non-ergodicity, which preserves the hierarchy of valleys but allows transitions and predicts a history-dependent behaviour, has been proposed by Ginzburg [19]. This more realistic picture is consistent with Palmer's approach [20], in which a cascade of bifurcations occurs on lowering the temperature.

Figure 7 [21] illustrates a hierarchical organization of valleys in the phase space. Each level represents

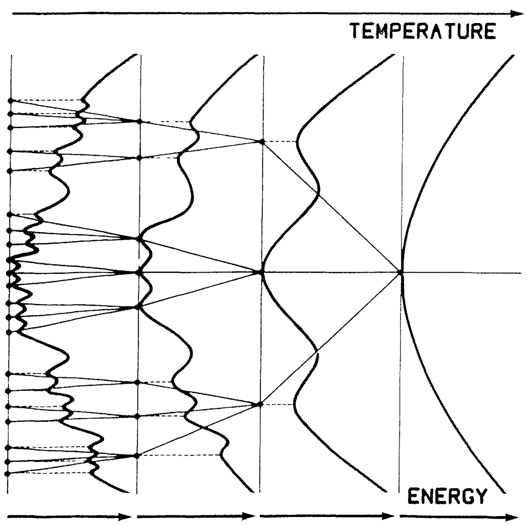

Fig. 7.-Illustration of a hierarchical organization of the energy valleys in the phase space. At each level, corresponding to a given temperature, the coarse-grained free energy surface is represented. When temperature is decreased, the valleys subdivide into others ; the structure of the surface remains the same at a lower scale.

the coarse-grained free energy surface at a given temperature ; on a fixed time scale (which allows the definition of the valleys), each valley subdivides into others when temperature is decreased. The above described experiment is very clearly accounted for within this scheme ; ageing at 0.72 T_g is a progressive statistical sampling of the valleys, e.g. at the lower level in figure 7. Annealing erases part of this evolution, since many valleys bunch together when temperature increases (higher levels in the figure). We have observed that, for a slight annealing at 0.78 T_g, only the short time processes of ageing have been reinitialized ; hence these short time processes correspond to the transitions occurring between valleys which are connected at the lower level in figure 7. The longer time relaxation corresponds to transitions (non-affected by annealing at 0.78 T_g) between valleys which are connected through a higher level. In contrast, annealing at 0.84 T_g involves these valley connections at a higher level in the hierarchical tree.

6. Conclusion.

Some characteristic features of the ageing effects in the $CdCr_{1.7}In_{0.3}S_4$ insulating spin-glass have been qualitatively specified. Two complementary kinds of measurements have been used :

i) low-frequency a.c. susceptibility measurements, in which the age (time elapsed since the sample was quenched below T_g) increases at constant observation time (inverse of the excitation frequency). These measurements are sensitive to the dynamics at short times as compared to the age.

ii) relaxation measurements of the thermo-remanent magnetization, which give access to longer observation times as compared to the age.

The observed ageing effects are not simply induced by the rapid crossing of T_g. A long stay at a temperature only slightly smaller than T_g before the final cooling to the measuring temperature does not in the least affect the subsequent relaxation curves.

The non-stationary response appearing in the a.c. susceptibility after a step of temperature cannot be ascribed to an effective unique spin temperature lagging behind the sample temperature. The evolution of the response does not, indeed, proceed along the quasi-equilibrium points defined by the long time susceptibility measurements at different temperatures.

The ageing effects are primarily due to the fact that the system has not reached its equilibrium state at the time of the measurements. They indicate that the cooling procedure brought the system into a quenched state which, at a given temperature, tends towards equilibrium within a very long time scale. The experiments described in the paper show that the spin-glass behaviour is quite different from that of ordered systems (e.g. Ising ferromagnets) quenched from $T >> T_c$ to $T < T_c$. In the ordered systems, the quenching effect results from the rapid crossing of the critical temperature T_c. Below T_c, any further temperature variation does not affect the general trend of the system towards equilibrium : it merely changes the characteristic time scale of this trend (thermal fluctuations favour the growth of the domains induced by quenching, see for instance [22,23]). In particular, let us transpose in an ordered system the experiment described in section 5, in which a stay at a higher temperature than the measuring temperature has been made during a small part of the waiting time : the corresponding relaxation would be that of a system at an effective age much greater than the total waiting time. During the stay at a higher temperature, the ordered system keeps on ageing in the same way as at the measuring temperature, but with a smaller characteristic time ; returning to the measuring temperature only slows down the process again. In the case of the spin-glass, this experimental procedure has brought the system to a different quenched state ; the short time ageing processes have been reinitialized, and the time range of the reinitialized processes increases when the temperature step becomes larger. In the spin-glass phase, each step decrease of the temperature leads to a different quenched state.

The observed behaviour is consistent with a picture in which new local energy minima appear at each decreasing step of temperature below T_g. In addition, the result of the experiment described in section 4 (memorization effect during a temperature decrease) supports the idea of a hierarchical organization of the energy valleys in the phase space, as has been suggested in several theoretical approaches. In order to fully clarify the ageing processes in spin-glasses, more systematic and quantitative experiments as well as progress in the theoretical models are needed ; to date, no approach of the spin-glass problem allows a quantitative description of the numerous results concerning ageing effects, and yet these effects appear as a direct consequence of the characteristic properties of the spin-glass phase.

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