Intermittent quakes and record dynamics in the thermoremanent magnetization of a spin-glass

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A method for analyzing the intermittent behavior of linear response data in aging systems is presented and applied to the spin-glass thermoremanent magnetization (TRM) data of Rodriguez et al. (Phys. Rev. Lett. 91, 037203, 2003). The probability density function (PDF) of the magnetic fluctuations has an asymmetric exponential tail, showing that the demagnetization process occurs through intermittent spin rearrangements or quakes which significantly differ from reversible fluctuations having a Gaussian distribution with zero average. The intensity of quakes is determined by the TRM decay rate, which in turn depends on the time since the initial quench and on the magnetic field, the time at which the magnetic field is cut. For a broad range of temperatures, these dependences are extracted numerically from the data and described analytically using the assumption that the system’s linear response is fully subordinated to the occurrence of the quakes which spasmodically release the imbalances created by the initial quench.

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INTRODUCTION

Many glassy materials unable to re-equilibrate after a temperature quench undergo aging, a dynamical process whose key properties are largely system independent. In spin-glasses, a class of disordered magnetic materials, one thoroughly investigated aging quantity is the thermoremanent magnetization (TRM) \[1\]. In a TRM experiment, a sample undergoes a rapid thermal quench at \(t = 0\), with a small magnetic field present. Subsequently, the temperature remains constant throughout the experiment, while the magnetic field is turned off in a single step at \(t = t_w\). The decay of the TRM for \(t > t_w\) depends mainly on the scaling variable \((t - t_w)/t_w\), where \(\mu\) is a parameter close to unity \[1\]. As recently recognized \[2, 3\], the value of \(\mu\) depends on the quenching rate, and approaches a so-called full aging limit, \(\mu = 1\), as the rate increases toward infinity, i.e. in the limit of an instantaneous quench. These phenomena together reveal a persistent memory of the initial quench and a strong sensitivity to the rate of cooling. Memory behavior includes a number of other fascinating aspects \[4, 5\], and could be rooted in a multi-scale, hierarchical nature of the energy landscape of amorphous systems \[6, 7, 8, 9, 10\].

Memory issues can be further elucidated by analyzing the fluctuations statistics in meso-scaled systems \[11, 12\], \[13, 14\]. The basic observation is that the Probability Density Function (PDF) of an aging quantity typically comprises a Gaussian part and an exponential tail. The Gaussian covers reversible fluctuations with zero average, and the tail describes intermittent events, which carry the drift of the aging process, e.g., in the present case, they carry the net change in magnetization. The intermittent events are prominent during the non-equilibrium aging regime \(t >> t_w\) where the Fluctuation Dissipation theorem is clearly violated \[12, 13, 15\]. Furthermore, as shown in the sequel, they are equally prominent in a short time interval immediately following field removal. In general, the statistical weight of intermittent fluctuations relative to the weight of Gaussian fluctuations is determined by the rate \(r_{TRM}\) of magnetization change, the latter depending on both \(t\) and \(t_w\) as detailed below.

Heat transfer statistics directly probes thermally activated dynamics, and is easily collected in numerical simulation. In two different aging systems, the Edwards-Anderson spin-glass model \[5, 15\] and a model with p-spin interactions \[16\], Gaussian and intermittent events are clearly identifiable. The idea that the intermittent events, or quakes are triggered by extremal, e.g. record sized, reversible fluctuations \[17, 18\], explains the age dependence of the PDF of energy fluctuations. The same ‘record dynamics’ approach was applied to the configuration autocorrelation function \[19\] and to dynamical properties of other complex systems \[20, 21\].

Arguably, quakes influence aging quantities other than the energy, including e.g. the all important linear response functions. Unlike the energy, response functions involve the turning of an external perturbation on or off, and hence require additional theoretical attention. In equilibrium situations, it is well known that a small perturbing field simply probes the spontaneous fluctuations of its conjugate variable. For out-of-equilibrium intermittency, an idea similar in spirit can be formulated as a subordination hypothesis: significant configuration changes, whether field induced, as in TRM, or spontaneous, as in the de-correlation of the magnetization fluctuations of an
unperturbed system, only occur in conjunction with the quakes. These, in turn, release the strain created by the initial quench in a temporal sequence which is, to linear order, unaffected by the perturbation. This subordination hypothesis was recently applied to the autocorrelation function in the Edwards-Anderson spin-glass in zero field \(^{19}\) and is presently applied to the experimental TRM decay. At a price—short time effects of equilibrium fluctuations are neglected—the approach leads to a considerable mathematical simplification, as the statistical properties of e.g. the response flow from those of the quakes.

In the sequel, we first describe the method of data analysis. We then show the intermittency of the decay and fit the age and time dependence of the TRM decay rate to a simple formula. The theoretical ideas behind this formula are spelled out in the Theory Section, and the whole paper is rounded off with a brief concluding Section.

Last but not least, a notational issue: the variable ‘\(t\)’ denotes here the time elapsed since the initial quench, or ‘age’, and ‘\(t_w\)’ denotes the specific age at which the external field is switched off. A slightly different convention, widespread in the experimental literature, see e.g. Refs. \(^{3, 22, 23}\), uses ‘\(t\)’ for the time elapsed after field removal, a quantity presently denoted by ‘\(t_{obs}\)’, with \(t_{obs} = t - t_w\). Furthermore, in Refs. \(^{15, 24}\), \(t_w\) is used to denote the system age, our present \(t\). Our choice emphasizes the initial quench as the common origo for all time variables, and slightly simplifies the notation, e.g. our scaling functions have a \(t/t_w\) rather than a \(1 + t/t_w\) argument.

**METHOD OF DATA ANALYSIS**

In this Section, the TRM data of ref. \(^{3}\) are analyzed with focus on intermittency. In the experiment, a Cu\(_{0.94}\)Mn\(_{0.06}\) sample, with critical temperature \(T_g = 31.5\,\text{K}\), is rapidly cooled, with an effective cooling time of 19s. The sample is then aged isothermally at temperature \(T\) in a weak magnetic field \((H = 20\,\text{G})\), with the field removed at \(t = t_w\). The TRM signal \(M(t)\) is measured for \(t > t_w\) and for different values of \(t_w\) and \(T\): \(t_w = 50, 100, 300, 630, 3600, 6310\) and 10000s and \(T = 0.4, 0.6, 0.83, 0.9\) and 0.95 \(T_g\). The observation time \(t_{obs} = t - t_w\) ranges from aprx. 6000s to aprx. 30000s and the ratio \(t/t_w\) correspondingly varies from 1 to 100. Measurements are recorded every 1.045s for \(t_w < 6310\)s and every 2.04s for \(t_w \geq 6310\)s. All data are given as dimensionless ratios of the TRM to the field cooled magnetization \(M_{FC}\).

We consider TRM changes \(\delta M\) over a small time interval \(\delta t\), i.e. from the data we calculate a time series of magnetization differences \(\delta M(i) = M(t_i + \delta t) - M(t_i)\), with \(t_i = t_{i-1} + \delta t\), and with \(\delta t << t\) chosen as a small multiplex of the measurement repeat time. The analysis has a twofold aim: estimating the PDF of the magnetization fluctuations in different situations in order to show the presence of intermittency, and estimating the time and age dependence of the rate \(r_{TRM}\) (henceforth simply ‘\(r\)’) of magnetization decay, in order to compare with theory.

The PDF are straightforwardly estimated by binning the \(\delta M(i)\) values sampled over suitable time intervals. An estimate of \(r_{TRM}\) is not easily obtained: in order to uncover the drift part of the dynamics, the Gaussian fluctuations, which are far more frequent than intermittent events over small time intervals, must be averaged out. Mainly, the averaging is done over suitably chosen subintervals of the observation interval. Additionally, we perform for \(T = 0.83T_g\) an average over an ensemble consisting of data with the same \(t/t_w\) value. From this ensemble we also construct the PDF of the magnetic fluctuations over a short time interval near \(t_w\).

For time averaging, we consider a set of intervals \(I_t = ([8/9]t, (10/9)t)\) with midpoints \(t\) equidistantly spaced on a logarithmic scale. The interval widths, \(0.22t\), are chosen as a compromise between the conflicting requirements of small statistical error and good temporal resolution. Using the values available in each interval \(I_t\), the average \(\mu_{SM}(t, t_w, \delta t)\) and the variance \(\sigma_{SM}^2(t, t_w, \delta t)\) of the magnetization change \(\delta M\) are estimated at time \(t\) using standard formulas. By varying \(\delta t\), we ascertain that \(\mu_{SM}\) is proportional to \(\delta t\). The proportionality constant, which is identical to \(r_{TRM}(t, t_w)\), is estimated by linear regression. The \(t\) and \(t_w\) dependence of \(r_{TRM}\) thus obtained is fitted to the expression predicted by record dynamics. As a final step, the dependence is integrated with respect to \(t\), leading to an analytical expression for the TRM decay, which is compared with the original data. The outcome of this whole procedure is displayed in the first five panels of Fig. \(^{2}\)

For ensemble averaging, we note that the \(t/t_w\) dependence of the TRM (full aging), which is established in the literature \(^{3}\) and confirmed by the present analysis, implies that \(\delta M\) values with the same \(t/t_w\), i.e. \(t/t_w = C\), are physically equivalent. Hence, they can meaningfully be collected from data streams taken at different \(t_w\) into ensembles labeled by the value of \(C\). This procedure is carried out for the \(T = 0.83T_g\) data, collecting, in each case, \(\delta M\) values within the interval \(t \in [Ct_w, 1.25Ct_w]\) and systematically varying the value of \(C\). From the \(C = 1.13\) ensemble, we construct the (unnormalized) PDF of \(\delta M\) data. We also estimate, for a number of different \(C\), the rate \(r_{TRM}(t, t_w)\) as the average of \(\delta M/\delta t\) of the corresponding ensemble. The results are shown in the main panel and the insert of Fig. \(^{3}\) respectively.
RESULTS

Figure 1 illustrates how TRM fluctuations $\delta M$ occurring over a small interval $\delta t$ have both a Gaussian component and an intermittent tail. The tail becomes more dominant as the average change $\mu_{\delta M}$ grows numerically larger. This differs from ‘normal’ transport, where increasing $\mu_{\delta M}$ would only shift the center of the Gaussian distribution away from zero.

Panel (a) of Fig. 1 compares two (unnormalized) PDFs of $\delta M$, which are both obtained from data with $T = 0.83 T_g$ and $t_w = 100s$. The $\delta M(i)$ values are collected over the same observation interval $I = [1000s, 4000s]$. The PDFs are shown on a logarithmic scale, where a Gaussian has a parabolic shape. The nearly Gaussian PDF (circles) is for $\delta t = 1.045s$ and the other PDF (diamonds) is for $\delta t = 5 \times 1.045s$. Increasing $\delta t$ increases the average magnetization change $\mu_{\delta M} = \delta t r_{TRM}$ and hence increases the amount of intermittency. Using positive $\delta M$ values, the central part of the PDF is fitted (full lines) to a Gaussian with zero average. Note how the Gaussian shape of the reversible fluctuations remains visible for positive $\delta M$ values, in spite of the strong intermittent left wing present for the larger $\delta t$ (diamonds).

Panel (b) of Fig. 1 shows the average $\mu_{\delta M}$ (squares) and the variance $\sigma_{\delta M}^2$ (diamonds), plotted versus $\delta t$. As $\mu_{\delta M}$ and $\delta t$ are expectedly proportional, the rate of magnetization decay, (averaged over the observation interval $I$) can be estimated as the slope $r_{TRM} = \mu_{\delta M}/\delta t$. The dotted line through the data illustrates the quality of the linear fit. For completeness, we also show the variance $\sigma_{\delta M}^2$. As one would expect in a large sample, $\sigma_{\delta M}$ is much smaller than the average.

Panels 1-5 of Fig. 2 illustrate the $t$ and $t_w$ dependence of the rate of magnetization $r_{TRM}$ for the five temperatures indicated. Error bars are obtained by standard methods and data points with (1σ) uncertainty larger than 10% are discarded. As it turns out, the rate approaches the functional form $r_{TRM} \propto a/t$ for large values of $t/t_w$, i.e. already for $t/t_w > 10$ this is the main contribution to $r_{TRM}$. Thus, $t r_{TRM} - a$ plotted versus $t/t_w$ describes the deviation of the rate from its asymptotic behavior. The full line depicts the function

$$y(t,t_w) = b_1 \left( \frac{t}{t_w} \right)^{\lambda_1} + b_2 \left( \frac{t}{t_w} \right)^{\lambda_2}.$$  \hspace{1cm} (1)

With parameters optimized by a least square error fit, this function offers a good analytical description of $r_{TRM}$. The form of the parameterization is justified theoretically in the next Section. Here we note that as $\lambda_2 < -3$, the second term of Eq. 1 only contributes for $t \approx t_w$, and that the sole parameter of importance in the limit $t >> t_w$ remains $a$, which, importantly, remains nearly constant through the temperature range.

Let us finally consider the change in magnetization $\Delta M$ over an observation interval $I = [t_i,t]$ starting at a time $t_i$ larger or equal to $t_w$, but otherwise arbitrary.
Plainly,

\[ \Delta M(t_i, t, t_w) = \int_{t_i}^{t} r_{TRM}(t', t_w) dt' = a \log(t/t_i) + \frac{b_1}{\lambda_1} \left[ \left( \frac{t}{t_w} \right)^{\lambda_1} - \left( \frac{t_i}{t_w} \right)^{\lambda_1} \right] + \frac{b_2}{\lambda_2} \left[ \left( \frac{t}{t_w} \right)^{\lambda_2} - \left( \frac{t_i}{t_w} \right)^{\lambda_2} \right]. \] (2)

For a generic observation interval, \( \Delta M \) is a function of three variables, as indicated. Customarily, one chooses \( t_i = t_w \), and indeed, for \( t_i = t_w = 100s \), the above formula yields the analytical approximation \( \Delta M(t, t_w) \) to the TRM decay plotted (blue circles) for selected values of \( t \), together with the measured data (red line) in the inserts of Fig. 2. Conforming to standard usage, the abscissa \( t/t_w - 1 \) is the ratio of the observation time to the field removal age. Note that the \( t_w \) dependent value of the magnetization at \( t = t_w \), formally an integration constant, is not provided by Eq. 2. This value is determined by shifting \( \Delta M(t, t_w) \) vertically, until they best overlap with the data is obtained. Finally, the asymptotic decay of the magnetization only acquires a \( t_w \) dependence if \( t_i = t_w \) is chosen.

The last panel of Fig. 2 shows the temperature dependence of the parameters \( a, \lambda_1 \) and \( \lambda_2 \). Remarkably for thermally activated dynamics, the value \( a = -0.01 \) works for all temperatures except for \( T = 0.95T_g \), i.e. very close to the critical temperature. This behavior has a simple interpretation: for \( t/t_w \) sufficiently large, each quake contributes, on average, the same amount to the TRM decay, and \( a \) is proportional to the logarithmic rate of quakes, \( \alpha \), which is \( T \) independent according to the theory. Finally, the temperature dependence of the two exponents \( \lambda_1 \) and \( \lambda_2 \) and of the corresponding pre-factors \( b_1 \) and \( b_2 \) (not shown), is smooth and rather weak, except near \( T_g \).

A property not previously noticed is the strong intermittency for \( t \approx t_w \). This is seen in the main plot of Fig. 2 where the (unnormalized) PDF (dots) of \( t_i/M/\delta t \) — \( a \) is collected from intervals \([t, 1.25t]\) with \( t/t_w = 1.13 \), using all available data streams with \( T = 0.83T_g \). The denominator \( \delta t \) is the repeat time of the measurement. The PDF features a Gaussian component and a strong intermittent component, as highlighted by fits (full lines) to a Gaussian with zero average (obtained from the positive data values), and an exponential (obtained from the negative data values). As a consistency check, we estimate the quantity \( t r_{TRM} - a \) as a function of \( t/t_w \). The insert shows this quantity (dots) with \( r_{TRM} \) estimated for each \( t/t_w \) as the average of \( \delta M/\delta t \) over the corresponding ensemble. The line—taken from the third panel of Fig. 2—is a fit obtained via time averages. The agreement shown between time and ensemble averages (except at very small values of \( t/t_w \)) confirms the validity of the time averaging procedure used to evaluate \( r_{TRM} \).

Summarizing, the fast magnetization decay occurring immediately after field removal is intermittent, a further indication that all magnetization decay is intermittent and controlled by the magnitude of \( r_{TRM} \). Secondly, time and ensemble averages give similar estimates of the magnetization rate.

**THEORY**

As it transpires from our results, the main theoretical focus will be on the rate of demagnetization \( r_{TRM} \), which appears intimately related to the intermittent events. In a record dynamics scenario \([17, 18]\), intermittent events, or *quakes*, reflect significant configurational changes which *(i)* lead from one metastable configuration to another, *(ii)* are irreversible and *(iii)* are triggered by extremal fluctuations. For thermal activated dynamics, these would be thermal fluctuations over record-sized energy barriers. We presently assume that quakes are statistically independent, and that measurable effects are all subordinated \([19]\) to their occurrence. The time and age dependence of any aging quantity is then co-determined by how many quakes occur between \( t_w \) and \( t \) and by the magnitude and nature of the physical changes that each quake entails. The number of quakes \( n_I \) in the observation interval, \((t_w, t)\), is a Poisson distributed stochastic variable \([17, 18]\) with average

\[ \langle n_I(t_w, t) \rangle = \alpha \log(t/t_w). \] (3)

The parameter \( \alpha \) depends linearly on the system size \([19]\), as it arises from an extensive number of independent contributions from different thermalized domains. Furthermore, it is temperature independent \([15]\), due to the implied self-similarity of the energy landscape of each thermalized domain \([16]\). While the above properties are supposedly generic \([17]\), the physical effects of the quakes could be system and even variable dependent. However, even without a specific knowledge of these effects, a sub-ordination hypothesis significantly restricts the possible age dependencies \([19]\), of physical quantities of interest.

Subordination means that any time dependence is mediated by \( n_I(t_w, t) \), whence the TRM magnetization becomes an (unknown) stochastic process with \( n_I \) acting as an effective ‘time’ variable. In principle, desired properties of the TRM can be found for fixed \( n_I \), and the underlying time dependencies can be re-introduced, by averaging \( n_I \) according to the Poisson distribution specified by Eq. 3.

As quakes are seldom events, we can treat their physical effects, e.g. magnetization or energy changes, as statistically independent. If the thermoremanent magnetization is treated as a Markov chain with \( n_I \) in the rôle of (discrete) time, its average \( M_{TRM}(n_I) \) admits an eigenvalue expansion \([22]\). According to Eq. 3, the range of \( n_I \) will be modest for achievable time arguments and
FIG. 2: (Color on line) Panels 1-5: the main plots show the estimated values of $t_{TRM} - a$ versus $t/t_w$, for $t_w = 50$ (right pointing triangles, unavailable for $T = 0.6T_g$ and $T = 0.9T_g$), 100 (circles), 300 (squares), 630 (diamonds), 1000 (pentagrams), 3600 (hexagrams), 6310 (asterisks) and (10000) (left pointing triangles). The lines are given by Eq. 1. The inserts compare the TRM decay measured at $t_w = 100s$ (red line), with the theoretical estimates (blue circles) obtained by integrating the fitted decay rate, see Eq. 2. The abscissa $t/t_w - 1$ is the ratio of the observation time to the field removal age. In panel 6, the parameter $a$ and the two exponents $\lambda_1$ and $\lambda_2$ are plotted vs. temperature. The lines are guides to the eye.
most terms in the aforementioned eigenvalue expansion
will effectively remain constant. To account for the few
modes which change during the decay, we tentatively
write $M_{TRM}(n_1) = c + c_0 \exp(a_0 n_1) + c_1 \exp(a_1 n_1) + c_2 \exp(a_2 n_1) + \ldots$ where $a_i$ are (real and negative) eigenvalues, all of order one or smaller. Without loss of generality, we can assume that for realistic values of $n_1$, $a_0 n_1$ remains sufficiently small to justify a linear expansion of the first exponential, leading to

$$M_{TRM}(n_1) = c' + c_0 a_0 n_1 + c_1 \exp(a_1 n_1) + c_2 \exp(a_2 n_1) + \ldots$$

(Average over $n_1$ yields)

$$M_{TRM}(t, t_w) = c' + c_0 a_0 \alpha \ln\left(\frac{t}{t_w}\right) + c_1 \left(\frac{t}{t_w}\right)^{\lambda_1} + c_2 \left(\frac{t}{t_w}\right)^{\lambda_2} + \ldots$$

(5)

where $\lambda_i = -\alpha (1 - e^{-\alpha}) < 0$ and $i = 1, 2$. Differentiating with respect to $t$, and re-arranging the terms, we finally obtain

$$t r_{TRM}(t) - c_0 a_0 \alpha = c_1 \lambda_1 \left(\frac{t}{t_w}\right)^{\lambda_1} + c_2 \lambda_2 \left(\frac{t}{t_w}\right)^{\lambda_2}.$$  (6)

The above expression has the same functional form as Eq. (1) with $a = c_0 a_0 \alpha$, $b_1 = c_1 \lambda_1$ and $b_2 = c_2 \lambda_2$. The weak $T$ dependence of both exponents and pre-factors should be expected as quakes are exothermic. The near $T$ independence of $\alpha$ implies, banning unlikely cancellations, that $\alpha$ is itself temperature independent, precisely as required by record dynamics.

All physical observables are simply related in the linear response regime [26]. E.g. the ‘relaxation rate’, which in the present notation is given by $S(t) = -\partial M_{TRM}/\partial \log(t - t_w)$, can be cast into the form $S(t_{obs}) = -t_{obs} r_{TRM}(t_{obs} + t_w)$, where, as we recall, $t_{obs} = t - t_w$. Inserting Eq. (6) for $r_{TRM}$ and plotting the outcome versus $\log_{10} t_{obs}$ reproduces the well known shape of $S(t)$: a broad maximum is present at $t_{obs} = t_w$, and a flat asymptotic value, equal to $a$, is reached for $t_{obs} \gg t_w$. The asymptotically logarithmic TRM decay and, equivalently, the constant asymptotic value of $S$ are widely observed in complex systems. To name a few cases, they are seen in switchable mirrors after UV illumination [27], in the field-cooled magnetization of spin glasses [28], and in the magnetic creep of the ROM model [29], of magnetic flux creep in type II superconductors [21]. In the asymptotic regime, the rate is $r_{TRM} \propto 1/t$, and the time at $t_w$ at which the perturbation is switched off is thus forgotten. Importantly, the energy decay rate of the EA spin glass [15] and of a p-spin model [10] is also (nearly) proportional the reciprocal of the age, $r_E(t) \propto 1/t$. (Recall that, inconveniently, the symbol $t_w$ is used in Refs. [15, 19] in lieu of $t$.) In conclusion, relaxation in response to the initial thermal quench, which is never forgotten, seems to emerge as the main physical process during non-equilibrium aging, whether or not an added field is present. This is fully consistent with the subordination assumption used to interpret the present data.

**SUMMARY AND CONCLUSIONS**

Using available spin-glass thermoremanent magnetization data and a general method of analysis, we have extracted the intermittent properties of the TRM decay and interpreted them theoretically using record dynamics. In combination with a previous investigation of the configuration autocorrelation function of the Edwards-Anderson spin-glass [19], the present results suggests that conjugate autocorrelation and response functions may inherit significant statistical properties from the quakes. This can lead to Fluctuation Dissipation-like relations [30] between the two, even in an out-of-equilibrium situation, once the transient effects of the field switch have died out.

The record dynamics approach melds real space features, i.e. the independent thermalized domains where quakes are initiated, with configuration space features, i.e. the scale invariance of the energy landscape associated to each domain, a concept repeatedly stressed in hierarchical models [3, 7, 8]. Similar ideas have been applied to ‘non-thermal’ dynamics, e.g. memory effects in driven...
dissipative systems are linked to the marginal stability of the attractors selected by the dynamics [18, 31, 32] and can also be understood by record dynamics. By construction, the description becomes invalid near the final equilibration time, since the postulate irreversibility of quakes cannot be maintained.

The complex interplay between external noise and drift in glassy dynamics is a pivotal issue in non-equilibrium statistical physics, and many of its aspects are still only partially understood. Further insights could be obtained by applying the present method to linear response functions in other situations, e.g. aging with a small temperature step. The intermittency of the heat loss has been studied in some detail in this situation [5], confirming that, in the Edwards-Anderson model, the largest energy barrier overcome in the past evolution sets the time scale for future intermittent events. One recent experimental finding is that the TRM signal loses its $t_w$ dependence in the extreme limit $t_w \gg t$ [33]. As proposed in that paper, the ‘post-aging’ decay is intrinsically related to the same mechanisms producing the usual aging effects, and is related to the memory of the initial state set up by the cooling procedure. We expect that experimental investigations of intermittency in mesoscopic-scaled systems will further elucidate this and other memory effects in complex dynamics.

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(Color on line) (a): The circles show the PDF of the magnetization change $\delta M$ for isothermal aging at $T = 0.83T_g$, with the field cut at $t_w = 100s$. The values of $\delta M$ are taken over short intervals $\delta t = 1.045s$ within the observation interval [1000, 4000]. Diamonds show the PDF of $\delta M$ from the same data stream, but now taken over larger intervals $\delta t = 3 \times 1.045s$. This leads to a much stronger intermittent component on the left wing of the PDF. The full lines are least square fits of the positive values of $\delta M$ to a Gaussian with zero average.

(b): From the same data, the average and the variance (the latter scaled as shown) of $\delta M$’s are plotted versus $\delta t$. The dotted line is obtained by a least square error fit.

Caption for Fig.2

(Color on line) Panels 1-5: the main plots show the estimated values of $t r_{TRM} - a$ versus $t/t_w$, for $t_w = 50$ (right pointing triangles, unavailable for $T = 0.6T_g$ and $T = 0.9T_g$), 100 (circles), 300 (squares), 630 (diamonds), 1000 (pentagrams), 3600 (hexagrams), 6310 (asterisks) and (10000) (left pointing triangles). The lines are given by Eq. 1. The insets compare the TRM decay measured at $t_w = 100s$ (red line), with the theoretical estimates (blue circles) obtained by integrating the fitted decay rate, see Eq. 2. The abscissa $t/t_w - 1$ is the ratio of the observation time to the field removal age. In panel 6, the parameter $a$ and the two exponents $\lambda_1$ and $\lambda_2$ are plotted vs. temperature. The lines are guides to the eye.

Caption for Fig.3

(Color on line) The main plot shows the unnormalized PDF (circles) of the quantity $\delta M/\delta t - a$. The values of $\delta M$ are collected from data streams taken with different $t_w$ and with $T = 0.83T_g$. The denominator $\delta t$ is the repeat time in each measurement, All data are taken within intervals $[t, 1.25t]$, where the value of $t$ changes with $t_w$, keeping a constant ratio $t/t_w = 1.13$. The parabola and the straight line are fits to a Gaussian and an exponential, respectively. The insert shows the $t/t_w$ dependence of $t r_{TRM} - a$ (dots), where $r_{TRM}$ is estimated by averaging $\delta M/\delta t$ over the ensemble of data points available at each $t/t_w$. The full line, which is lifted from the third plot of Fig. 2, is obtained using a different averaging procedure, and is therefore not a direct fit to the data shown.