Aging Effect in Ceramic Superconductors

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A three-dimensional lattice of the Josephson junctions with a finite self-conductance is employed to model ceramic superconductors. By using Monte Carlo simulations it is shown that the aging disappears in the strong screening limit. In the weak screening regime, aging is present even at low temperatures. For intermediate values of the self-inductance, aging occurs in an intermediate temperature interval but is suppressed entirely at high and low temperatures. Our results are in good agreement with experiments.

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The off-equilibrium dynamical properties of glassy systems have attracted the attention of researchers for many years. In particular, aging phenomena observed in spin glasses [1] have been studied both theoretically [2] and experimentally [3] in detail. In the aging phenomenon the physical quantities depend not only on the observation time but also on the waiting time, t_w, i.e., how long one waits at constant field and temperature before measurements. The origin of such memory phenomena relates to the rugged energy landscape which appears due to disorder and frustration [4].

Recently, the aging effect was observed in the ceramic superconductor $Bi_2Sr_2CaCu_2O_8$ by Papadopoulou *et al.* [5] monitoring the zero field cooled (ZFC) magnetization. The relaxation of the ZFC magnetization has been measured by cooling the sample in zero field to the measuring temperature, allowing the sample to stay at that temperature for a certain time t_w and then applying the probing field and recording the change of the magnetization with observation time at constant temperature. Papadopoulou *et al.* made two key observations. First, the aging effect is not observed at high fields and at high temperatures. Second, *at low temperatures this effect disappears again*. Thus the aging phenomenon exists only for weak enough fields and in an intermediate temperature region. The first observation is trivial because at high fields or high temperatures the roughness of the energy landscape does not play any crucial role and the system loses its memory. Since at low temperatures the role of the energy landscape becomes important, the second result of Ref. [5] is not trivial from the point of view of the standard spin glass theory. Papadopoulou *et al.* suggested that at low temperatures the external field is screened from the bulk of the sample and it cannot probe the collective behavior of the Josephson junction network. One of the aims of our paper is to check if this idea is correct.

It should be noted that, in addition to the aging effect, the paramagnetic Meissner effect (PME) [6] was also observed in the investigated $Bi_2Sr_2CaCu_2O_8$ compound [5]. This result is important for the following reason. It is well known that the PME in ceramic superconductors may be explained based on the existence of π junctions in the Josephson network [7]. Such π junctions could arise naturally as a consequence of d-wave pairing of the superconducting order parameter. One of the potential candidates for this pairing is the $d_{x^2-y^2}$ state. Despite the fact that the existence of π junction was confirmed experimentally by a scanning SQUID microscope [8], only the detection of the PME does not unambiguously support the d-wave symmetry because PME has also been observed in conventional superconductors [9]. However, the combined observation of aging and the PME in the same material does yield support for the existence of d-wave superconductivity.

In order to explain the experiments [5] we use a model for the d-wave superconductivity in a Josepson junction network [10]. By using Monte Carlo simulations we demonstrate that there are three screening regimes for the aging phenomenon. In the strong screening limit the aging is suppressed at any temperature. In the weak screening regime it is observable even at low temperatures. The intermediate screening regime is found to be the most interesting: here the aging is present only in an intermediate temperature interval; it does not appear at low temperatures. This is precisely what was observed in the experiments [5]. The underlying mechanism of aging is twofold: the screening makes the energy landscape less rough and the external magnetic field is screened from the bulk. The latter effect is strong at low temperatures and at high values of the inductance.

We neglect the charging effects of the grain and consider the following Hamiltonian [10,11]:

$$\mathcal{H} = -\sum_{\langle ij\rangle} J_{ij}\cos(\theta_i - \theta_j - A_{ij}) + \frac{1}{2L}\sum_p (\Phi_p - \Phi_p^{\mathrm{ext}})^2, \quad (1)$$

$$\Phi_p = \frac{\phi_0}{2\pi}\sum_{\langle ij\rangle}^{p} A_{ij}, \qquad A_{ij} = \frac{2\pi}{\phi_0}\int_i^j \vec{A}(\vec{r})\cdot d\vec{r},$$

where θ_i is the phase of the condensate of the grain at the ith site of a simple cubic lattice, $\vec{A}$ is the fluctuating gauge potential at each link of the lattice, ϕ_0 denotes the flux quantum, J_{ij} denotes the Josephson coupling between the ith and jth grains, L is the self-inductance of a loop (an elementary plaquette), while the mutual inductance between different loops is neglected. The first sum is taken over all nearest-neighbor pairs and the second sum is taken over all elementary plaquettes on the lattice. Fluctuating variables to be summed over are the phase variables, θ_i, at each site and the gauge variables, A_{ij}, at each link. Φ_p is the total magnetic flux threading through the pth plaquette, whereas Φ_p^{ext} is the flux due to an external magnetic field applied along the z direction,

$$\Phi_p^{\mathrm{ext}} = \begin{cases} HS & \text{if } p \text{ is on the } \langle xy \rangle \text{ plane} \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

where H and S denote the external magnetic field and the area of an elementary plaquette, respectively. In what follows we assume J_{ij} to be an independent random variable taking the values J or $-J$ with equal probability ($\pm J$ or bimodal distribution), each representing 0 and π junctions.

It should be noted that the model (1) captures not only the PME [10,11] but also several dynamical phenomena of ceramic high-T_c superconductors, such as the anomalous microwave absorption [12], the so-called compensation effect [13], the effect of applied electric fields in the apparent critical current [14], and the ac resistivity [15]. Similar to the spin glass case, the frustration due to the random distribution of π junctions should lead to a multivalley energy landscape with energy barriers separating different metastable states. Such a rugged energy landscape would favor the aging effect in the model (1). In fact, an extensive Monte Carlo simulation by Kawamura and Li [16] revealed that the model (1) in zero field exhibits an equilibrium phase transition with a broken time-reversal symmetry into the novel "chiral glass" state. In this chiral glass phase, "chiralities," or local loop supercurrents circulating over grains carrying a half flux quantum, are frozen in a spatially random manner.

The dimensionless magnetization along the z axis normalized per plaquette, M, is given by

$$M = \frac{1}{N_p \phi_0} \sum_{p \in \langle xy \rangle} (\Phi_p - \Phi_p^{\mathrm{ext}}), \tag{3}$$

where the sum is taken over all N_p plaquettes on the $\langle xy \rangle$ plane of the lattice. The dimensionless field h and inductance $\tilde{L}$ are defined as follows:

$$h = \frac{2\pi HS}{\phi_0}, \qquad \tilde{L} = (2\pi/\phi_0)^2 JL. \tag{4}$$

The parameter $\tilde{L}$ controls different screening regimes: the larger the $\tilde{L}$, the stronger the screening.

In order to study the aging effect in the ZFC regime we quench the system from a high temperature to the working temperature. There the system is evolved in zero field during a waiting time, t_w. Then the external field h is turned on and the subsequent growth of the magnetization $M(t, t_w)$ is monitored. The free boundary conditions are implemented (the magnetization always vanishes for the periodic boundary conditions [10,11]).

We have checked the finite size effect for three-dimensional systems of linear sizes $l = 12$, 24, and 36. Since this effect is not substantial we will present the results for $l = 24$. Following experiments [5], we chose observation times to be of order t_w. Figure 1 shows the dependence of the magnetization on t and t_w for $l = 24$, $\tilde{L} = 1$, and $h = 0.25$ and 0.05 for several typical temperatures (measured in units of J). Note that for this inductance the chiral glass transition takes place at $T \simeq 0.286$ [16]. The time is measured in the number of Monte Carlo steps (MCS). For $h = 0.05$ (left panel) the aging effect disappears at high temperatures. The screening effect is visible at low T's but it is not strong enough to suppress the aging effect entirely. One may think that the screening would become more important for stronger fields and the aging would not occur at low temperatures. Our results for $h = 0.25$ (right panel) show, however, that this is not the case. In what follows we will focus on $h = 0.05$, because a twice-as-small value of h does not change the results in any substantial way. We found that for $\tilde{L} < \tilde{L}_1^*$ (weak screening regime), where the borderline value $\tilde{L}_1^* = 3.5 \pm 0.5$, one has the standard scenario: the aging disappears only at high temperatures.

Figure 2 shows the results for $\tilde{L} = 7$. In agreement with the experiments [5], the aging effect appears only for the intermediate temperature interval. At low T's the effect is suppressed due to the screening of the magnetic field from the bulk. This is the main result of this Letter.

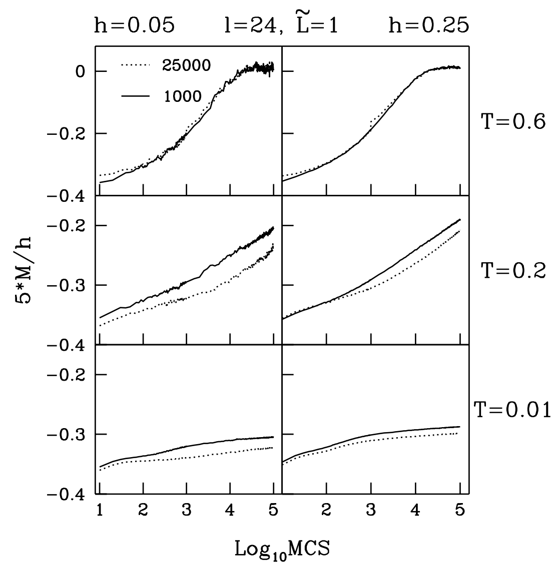

FIG. 1. The temperature and time dependence of M for $t_w = 1000$ (solid lines) and $t_w = 25\,000$ (dotted lines). $l = 24$, $\tilde{L} = 1$, and $h = 0.25$ and 0.05. The results are averaged over 60–120 samples.

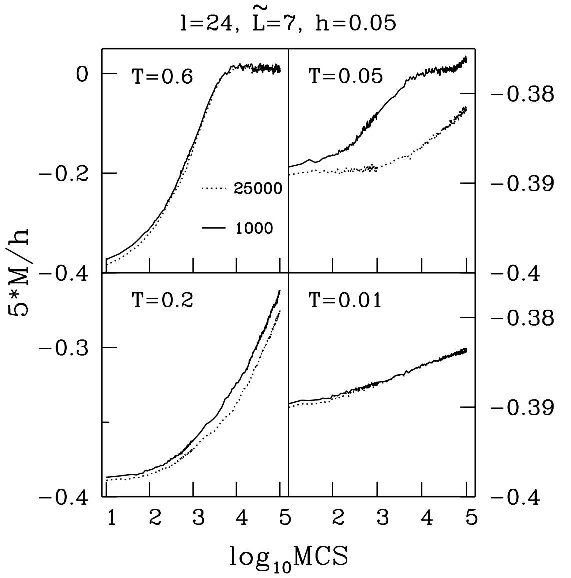

FIG. 2. The temperature and time dependence of M for $t_w = 1000$ and $t_w = 25\,000$. $l = 24$, $\tilde{L} = 7$, and $h = 0.05$. The results are averaged over 60–120 samples.

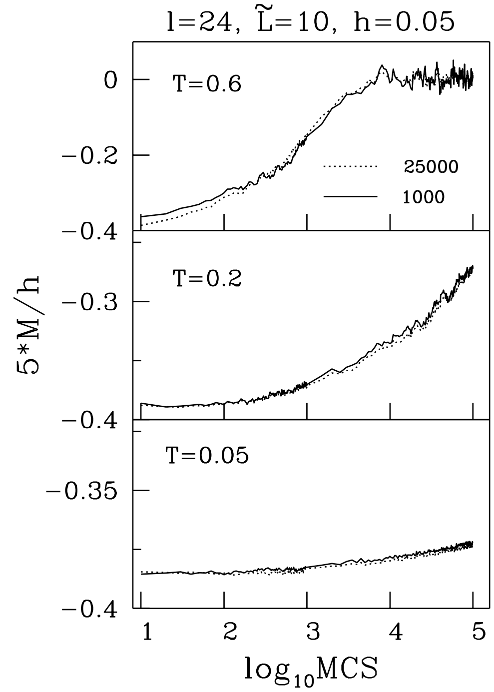

FIG. 3. The temperature and time dependence of M for $t_w = 1000$ and $t_w = 25\,000$. $l = 24$, $\tilde{L} = 10$, and $h = 0.05$. The results are averaged over 120–240 samples.

We have found that the nonstandard scenario is observed for $\tilde{L}_1^* < \tilde{L} < \tilde{L}_2^*$, where the borderline value $\tilde{L}_2^* = 9.0 \pm 0.5$. For this interval of $\tilde{L}$ the aging effect disappears at temperatures $T \leq T^* = 0.02 \pm 0.01$. Our results have been obtained for the observation times comparable with the waiting times, but we believe that they should be valid for longer observation time scales. It should be stressed that the experimental finding of Papadopoulou *et al.* [5] cannot be explained by the standard *XY* model, where the screening effect is not taken into account.

One can demonstrate that in the strong screening limit $\tilde{L} > \tilde{L}_2^*$ the aging effect does not occur at any temperature because the external field is screened entirely. It may be seen in Fig. 3, where the results for $\tilde{L} = 10$ are presented. The present model exhibits a finite-temperature chiral glass ordering for $\tilde{L} < \tilde{L}_c^{\mathrm{CG}}$ (the superscript means the chiral glass), where $\tilde{L}_c^{\mathrm{CG}} = 6 \pm 1$ [16]. Since $\tilde{L}_2^* > \tilde{L}_c^{\mathrm{CG}}$ the aging effect is suppressed in the region where the chiral glass phase is not favored. The PME is, however, observed for any strength of screening [11]. The observation of both the PME and the aging phenomenon supports the hypothesis about the existence of π junctions (and d-wave pairing) because the two effects cannot occur simultaneously in the flux compression picture for the PME [17].

Figure 4 shows the results for $T = 0.2$ and different values of h. In agreement with the experiments [5], the aging effect gets more and more suppressed as the field increases. For sufficiently large magnetic fields, $h > 1$, this effect is no longer observable.

The question we ask now is what is the mechanism of aging behavior in our model? We have studied the spatial distribution of flux, $\tilde{\Phi}(r)$, inside the sample [the definition of $\tilde{\Phi}(r)$ is given in Ref. [11]]. Figure 5 shows such distribution obtained as an averaged $\tilde{\Phi}(r)$ over the observation time and over four equivalent directions along $\pm x$ and $\pm y$ axes. Here r is a distance from the surface in units of lattice spacing. For a fixed screening strength the magnetic field is expelled more and more from the bulk as T is

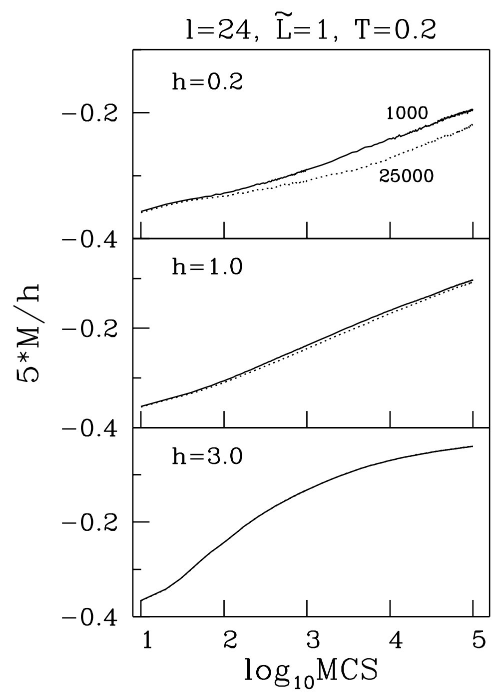

FIG. 4. The field and time dependence of M for $t_w = 1000$ and $t_w = 25\,000$. $l = 24$, $\tilde{L} = 1$, and $T = 0.2$. The results are averaged over 20–60 samples.

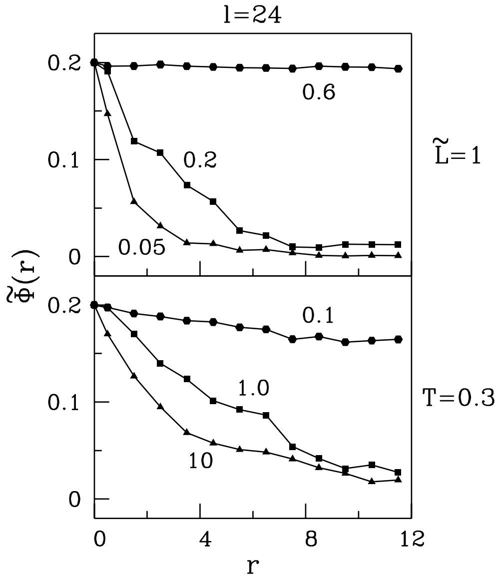

FIG. 5. Spatial flux distributions for several values of T and $\tilde{L}$. The upper panel corresponds to $\tilde{L} = 1$ and $T = 0.6$, 0.2, and 0.05. The values of T are shown next to the curves. The lower panel corresponds to $T = 0.3$ and $\tilde{L} = 0.1$, 1, and 10. The values of $\tilde{L}$ are shown next to the curves. We take $l = 24$ and $h = 0.2$. Depending on T and $\tilde{L}$ the results are averaged over 30–50 samples.

lowered. Therefore, for the strong enough screening, one could not observe the aging at low T's. The results in the lower panel of Fig. 5 show that the stronger the screening the weaker the penetration of the field into the sample. Consequently, the aging effect should be suppressed in the strong screening limit. Three distinct scenarios of the aging phenomenon may be understood qualitatively based on the flux distribution inside the sample.

We also explored the effect of screening on the energy landscape. Our preliminary studies of local minima at $T = 0$ show that the energy landscape gets smoother as the screening is increased [18] and the glassy effects become less pronounced.

In conclusion, our study reveals that screening has a strong influence on the aging phenomenon. For $\tilde{L}_1^* < \tilde{L} < \tilde{L}_2^*$, aging appears only at intermediately high temperatures. This nontrivial behavior agrees with recent experimental results for a ceramic superconductor. The study of the aging effect sheds new light on the important problem about the nature of the symmetry of the superconducting order parameter. On the other hand, the aging effect was also found to have a strong correlation with the occurrence of the chiral glass phase. Experimental search for this phase would be of great interest.

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