AGING EFFECT IN CERAMIC SUPERCONDUCTORS

Mai Suan Li$^{1,2}$, Per Nordblad$^3$ and Hikaru Kawamura$^4$

$^1$Institute of Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, Poland
$^2$Institut für Theoretische Physik, Universität zu Köln, Zülpicher Straße 77, D-50937 Köln, Germany
$^3$Department of Materials Science, Uppsala University, Box 534, S-751 21 Uppsala, Sweden
$^4$Department of Earth and Space Science, Faculty of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan

A three-dimensional lattice of the Josephson junctions with a finite self-conductance is employed to model ceramic superconductors. 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 at intermediate temperatures interval but is suppressed entirely at high and low temperatures. Our results are in good agreement with experiments.

PACS numbers: 75.40.Gb, 74.72.-h

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 have been studied both theoretically and experimentally 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.

Recently, the aging effect has been observed in the ceramic superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ by Papadopoulou et al 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 have 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 looses its memory. Since at low temperatures the role of the energy landscape becomes important, the second result of Ref. 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.

It should be noted that in addition to the aging effect also the paramagnetic Meissner effect (PME) was observed in the investigated Bi$_2$Sr$_2$CaCu$_2$O$_8$ compound. 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 $\pi$-junctions in the Josephson network. Such $\pi$-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 $\pi$-junction was confirmed experimentally by a scanning SQUID microscope, only the detection of the PME does not unambiguously support the $d$-wave symmetry because PME has been also observed in conventional superconductors. 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 we use a model for the $d$-wave superconductivity in a Josephson junction network. 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: the aging is here present only in an intermediate temperature interval, it does not appear at low temperatures. This is precisely what was observed in the experiments. 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

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

where $J_{ij}$ is the Josephson coupling, $A_{ij}$ is the magnetic flux through the junction, $\theta_i$ and $\theta_j$ are the phase angles, $\Phi_p$ is the magnetic flux through the $p$-th junction, and $\Phi_p^{ext}$ is the external magnetic field applied to the $p$-th junction.
\[
\Phi_p = \frac{\phi_0}{2\pi} \sum_{<ij>} A_{ij} \text{, } A_{ij} = \frac{2\pi}{\phi_0} \int_i^j \vec{A}(\vec{r}) \cdot d\vec{r} ,
\]
(1)

where \(\theta_i\) is the phase of the condensate of the grain at the \(i\)-th site of a simple cubic lattice, \(\vec{A}\) is the fluctuating gauge potential at each link of the lattice, \(\phi_0\) denotes the flux quantum, \(J_{ij}\) denotes the Josephson coupling between the \(i\)-th and \(j\)-th 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, \(\theta_i\), at each site and the gauge variables, \(A_{ij}\), at each link. \(\Phi_p\) is the total magnetic flux threading through the \(p\)-th plaquette, whereas \(\Phi_{ext}^p\) is the flux due to an external magnetic field applied along the \(z\)-direction,

\[
\Phi_{ext}^p = \begin{cases} 
HS & \text{if } p \text{ is on the } <xy> \text{ plane} \\
0 & \text{otherwise} 
\end{cases} , 
\]
(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 \(\pi\) junctions.

Similar to the spin glass case, the frustration due to the random distribution of \(\pi\)-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 of Monte Carlo simulation by two of the authors [10] has 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

\[
M = \frac{1}{N_p \phi_0} \sum_{p \in <xy>} (\Phi_p - \Phi_{ext}^p) ,
\]
(3)

where the sum is taken over all \(N_p\) plaquettes on the \(<xy>\) plane of the lattice. The dimensionless field \(h\) and inductance \(\tilde{L}\) are defined as follows

\[
h = \frac{2\pi HS}{\phi_0} , \quad \tilde{L} = (2\pi/\phi_0)^2 JL.
\]
(4)

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

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].

In order to study the aging effect in the zero field cooled (ZFC) regime we quench the system from a high temperature to the working temperature. The system is then 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 [3], we choose observation times to be of order of \( t_w \). Fig. 1 shows the dependence of the magnetization on \( t \) and \( t_w \) for \( l = 24, \tilde{L} = 1, h = 0.25 \) and 0.05 for several typical temperatures (measured in units of \( J \)). Note that for this inductance the chiral glass transition takes place at \( T \simeq 0.286 \) [1]. 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 have 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.

![FIG. 3. The temperature and time dependence of \( M \) for \( t_w = 1000 \) and \( t_w = 25000 \). \( l = 24, \tilde{L} = 10 \) and \( h = 0.05 \). The results are averaged over 120 – 240 samples.](image)

For \( L > \tilde{L}_2^* \) (weak screening regime), where the borderline value \( \tilde{L}_2^* = 7 \), 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 the present paper. We have found that the non-standard 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 ones but we believe that they should be valid for longer observation time scales. It should be stressed that the experimental finding of Papadopoulo et al. [3] 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 an finite-temperature chiral glass ordering for \( \tilde{L} < \tilde{L}_{CG}^* \) (the superscript means the chiral glass), where \( \tilde{L}_{CG}^* = 6 \pm 1 \) [13]. Since \( \tilde{L}_2^* > \tilde{L}_{CG}^* \) 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 [1]. The observation of both the PME and the aging phenomenon supports the hypothesis about the existence of \( \pi \)-junctions (and \( d \)-wave pairing) because the two effects cannot occur simultaneously in the flux compression picture for the PME [17].

![FIG. 4. The field and time dependence of \( M \) for \( t_w = 1000 \) and \( t_w = 25000 \). \( l = 24, \tilde{L} = 1 \) and \( T = 0.2 \). The results are averaged over 20 – 60 samples.](image)
spatial distribution of flux, $\tilde{\Phi}(r)$, inside the sample (the
definition of $\tilde{\Phi}(r)$ is given in Ref. [11]). Fig. 5 shows such
distribution obtained as an averaged $\tilde{\Phi}(r)$ over the ob-
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 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
screening the weaker penetration of the field into the sam-
ple. 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 have also explored the effect of screening on the en-
ergy 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
would become less pronounced.

In conclusion, our study reveals that screening has a
strong influence on the aging phenomenon. For $L^*_1 <
L < L^*_2$, aging appears only at intermediately high tem-
peratures. This non-trivial behaviour agrees with recent
experimental results for a ceramic superconductor. The
study of the aging effect sheds new light on the impor-
tant 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 correla-
tion with the occurrence of the chiral glass phase. Exper-
imental search for this phase would be of great interest.

Financial support from the Polish agency KBN (Grant
number 2P03B-025-13 and Grant number 2P03B-146 18)
is acknowledged. MSL thanks T. Nattermann for the
warm hospitality at the Institute for Theoretical Physics,
Cologne University.

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 $L$ are shown next to the curves. We take $l = 24$
and $h = 0.2$. Depending on $T$ and $L$ the results are averaged
over 30 - 50 samples.

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V. Moshchalkov, X. G. Qui, and V. Bruyndoncz, Phys. Rev. B 55, 11793 (1997).

[18] M. S. Li, unpublished.