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Unusual noise in the magnetization relaxation in MgB_2 superconductors

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Magnetization relaxation studies have been made on MgB_2 powders as a function of magnetic field and temperature. An H-T phase diagram is constructed representing different regimes of flux dynamics. It is found that at high temperature and field the magnetization relaxation, $m(t)$ is logarithmic and follows the Anderson-Kim behavior. At low T ($T<10$ K) and moderate fields (4 kOe$<H<$8 kOe), it becomes nonlogarithmic. The most interesting region of flux creep is, however, at low T and low H, where it is observed that the magnetization at fixed field and temperature becomes noisy. The noise levels are much larger than our superconducting quantum interference device resolution.

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The recent discovery of superconducting[1] MgB_2 with transition temperature $T_c \sim 39$ K, has drawn the attention of many researchers. It has revitalized the interests of both theoretical and experimental activities. There are many proposals for potential application of MgB_2, exploiting its high T_c and critical current density (J_c). However, for all potential applications one needs to understand the pinning properties to get the optimum values of J_c's and critical fields (H_c). Recently, nonstoichiometeric compositions of MgB_2 have also been reported.[2,3] Zhu *et al.*[3] have performed detailed analysis of microstructure and structural defects in MgB_2 superconductors. They were able to identify stacking faults, dislocations, and second phase particles. Bugoslavsky *et al.*[4] and Wen *et al.*[5] have studied the vortex dynamics in the new MgB_2 superconductors, and determined the dynamic magnetization relaxation rate by studying different field sweep rates. In addition they have also constructed the vortex phase diagram, determining the irreversibility field and the quantum vortex melting. Recently reported magneto-optic images[6] (MO) and magnetization loops[5–8] have shown a non-critical-state-type flux penetration in low fields at low temperature. The observations by these authors show that the flux in these materials enters in the form of microavalanches. These observations indicate a complex underlying pinning mechanism in MgB_2 superconductors and call for further investigations of the low-field flux dynamics.

In this work we present magnetic relaxation studies on MgB_2 superconductors. The data were taken in a conventional way, i.e., the applied field was increased to a desired value and held constant, then the magnetization as a function of time was recorded for approximately an hour for each set of data. The samples were prepared using the solid-state reaction method with Mg and B powders mixed in stoichiometric composition. The powders were then wrapped in a Ta foil and sealed in a quartz tube under low Ar pressure and heated to 925 °C for approximately 2 h. The correct phase was identified with x rays. No secondary phases were detected. All magnetic measurements were performed in a Quantum Design MPMS superconducting quantum interference device (SQUID) magnetometer. The dc susceptibility as a function of temperature showed a T_c of 38 K. For the magnetization measurements, the sample powder was passed through a sieve of 75 μm to reduce the particle size and thus ensure that particles of uniform size are selected for the measurements. The powder sample also ensures that the contributions from weak link effects in the measurements are small.

To obtain the relaxation data the sample was zero field cooled, the field was then increased to a desired value and the magnetization was recorded for approximately 1 h. At $T=20$ K the relaxation was obtained for different fields ranging from 500 to 12 000 Oe. The observed relaxation data at this temperature and different fields show a typical logarithmic relaxation of the Anderson-Kim[9] type. The magnetic relaxation is fitted to the following expression:

$$m(t)=m(0)\left[1-S\ln\left(1+\frac{t}{\tau}\right)\right],$$

where $m(0)$ is the initial magnetization, τ is the system time constant, and $S=[1/m(0)]\partial m/\partial \ln t$, is the normalized relaxation rate. In the Anderson-Kim (critical state) model the normalized relaxation rate is given as $S \sim kT/U_0$, where U_0 is the pining potential height and k is the Boltzmann constant.

The relaxation rates obtained from the fit are plotted in Fig. 1. It is evident in Fig. 1 that the relaxation rate increases monotonically with increasing field. The variation in the relaxation rate is very slow initially, i.e., for a field change from 4000 to 10 000 Oe, S changes from 0.004 to 0.01, how-

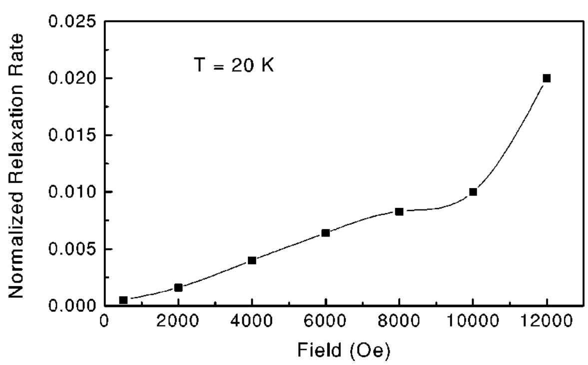

FIG. 1. The variation of the normalized relaxation rate $S=[1/m(0)](dm/d\ln t)$ with field while the temperature was held constant at $T=20$ K.

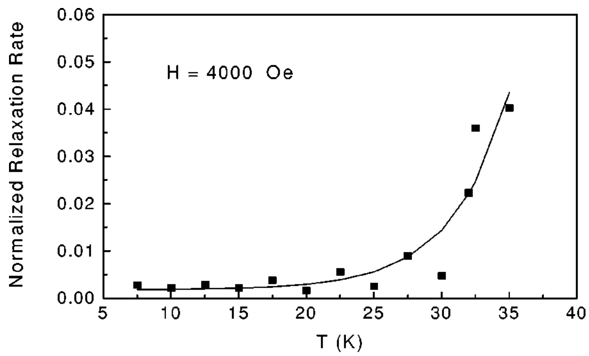

FIG. 2. The temperature dependence of the normalized relaxation rate at $H=4$ kOe.

ever, variations in the relaxation rate are enhanced when magnetic field exceeds 10 kOe. It is worth mentioning here that the observed relaxation rate is much lower than those reported for high-T_c cuprate superconductors and that it shows the strong pinning typical of Nb_3Sn-like superconductors.

The relaxation rates at different temperatures and a fixed field of 4 kOe are plotted in Fig. 2. It is clear that S remains constant up to high temperature ($\sim$20 K) and then rises steeply. A very slow and temperature-independent relaxation rate in the range 5–20 K indicates a very strong pinning and a minimum role being played by thermal fluctuations. The temperature-independent relaxation rate could arise from the quantum creep effects, the collective pinning, and/or the distribution of the pinning potential heights.[10] The temperature-independent and nonzero relaxation rate presented here extends to a very high temperature ($T\sim20\,\mathrm{K}$) and is hard to explain on the basis of quantum effects at that temperature. Previous studies have shown the quantum creep effects only in the very low temperature range.[11]

We have also studied the relaxation effects at low fields. The interesting behavior of the magnetic relaxation in MgB_2 is that it follows three different regions in the H-T plane. The $m(t)$ follows a logarithmic form at high T and H, whereas, at low T (below about 10 K), and moderate H, the relaxation becomes nonlogarithmic and still at lower temperature and at least for the low field ($H<3000\,\mathrm{Oe}$), the relaxation becomes very noisy. It is further observed that, at low temperature, as one increases the applied field, the noise in the magnetization reduces and a nonlogarithmic relaxation appears, and on further increasing the field, it becomes logarithmic. In Fig. 3(a)–(c), we have plotted magnetization relaxation at 5 K, as a function of time for approximately 1 h and for three different fields. The data have been normalized to the initial magnetization value, $m(0)$, so that the curves are visible in the same graph. Three different regions of flux creep are evident in the figure, as discussed above. In Fig. 4, we have plotted the magnetization relaxation at three different temperatures and a fixed field of 400 Oe. Note that in these measurements the field was cycled to ±10 kOe prior to relaxation measurements. A noise similar to the one in Fig. 3(a) is also apparent at 7.5 K, and 10 K. The amplitude of the noise decreases with increasing temperatures.

Many authors have addressed the nonlogarithmic decay of magnetization previously, at least for the high-temperature superconductors. In this regime, the magnetization follows the interpolation formula suggested for the collective creep theory:[10]

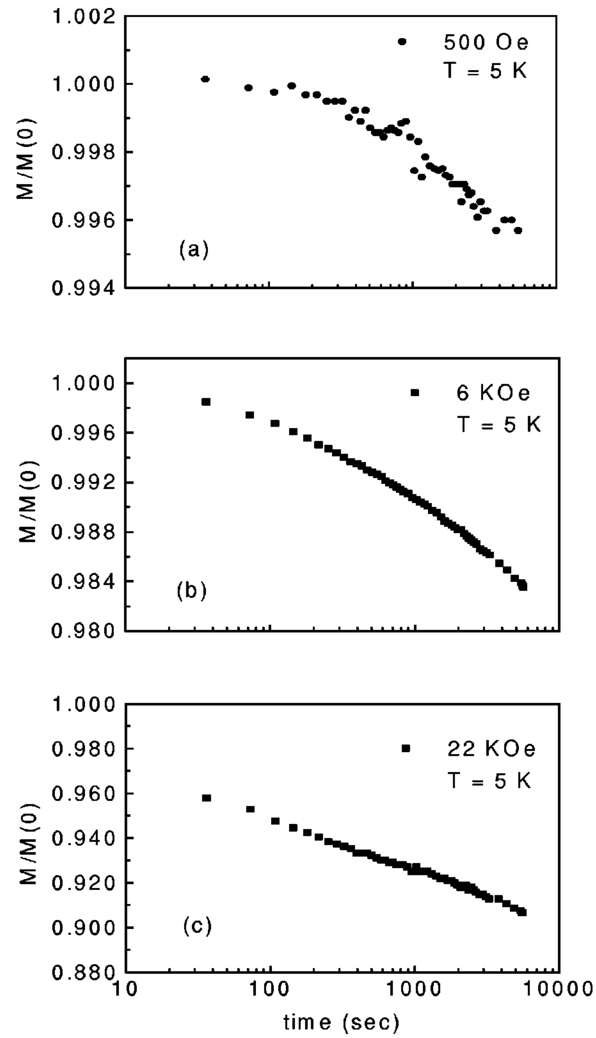

FIG. 3. The time dependence of the magnetization at $T=5$ K for three different fields. (a) $m(t)$ at low fields, $H=0.5$ kOe; a large noise is evident. (b) At 6 kOe the noise disappears and a nonlogarithmic $m(t)$ is evident. (c) $m(t)$ at higher fields showing logarithmic relaxation.

$$m(t)=m(0)\left\{1-\frac{\mu kT}{U_0}\ln\left(\frac{t}{\tau}+1\right)\right\}^{-1/\mu}.$$

Here, $\mu\sim\frac{1}{7}$ is the collective pinning critical exponent; all other parameters have a similar meaning as mentioned previously. Our results show a good fit of the data for collective pinning at this temperature and these fields (not shown in the figure).

Before we address the noise in the relaxation, we establish that our measurements are not the artifact of any field inhomogeneity. It is known for sometime that SQUID magnetometers may have field inhomogeneity while scanning the sample;[12] the problem is more serious when taking magnetization in superconductors due to the shielding currents. To

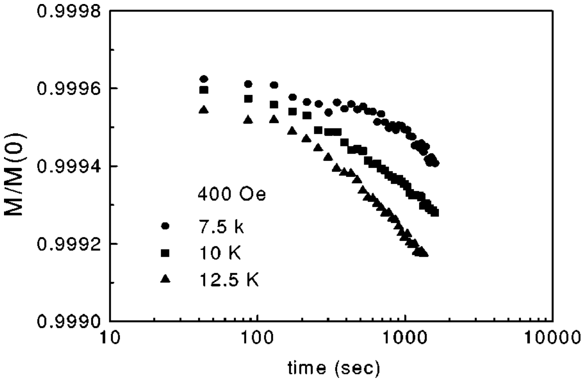

FIG. 4. Magnetization relaxation for approximately 20 min at $H=400$ Oe and at three different temperatures as indicated. These curves were obtained on nonvirgin loops, i.e., the field was cycled to ± 10 kOe prior to relaxation measurements.

cater these Ravikumar *et al.*[13] have proposed what is called a half-scan method (see reference for details); we have employed this method in some of our measurements to see if the noise is not the artifact of any field inhomogeneity. We find that despite the improved algorithm, a noise in the magnetic relaxation still persists. This indicates that the measured effect is true and not the artifact of any field inhomogeneities.

Finally, to explain the low-T and -H behavior of the relaxation data we refer to the low-temperature magnetization loop obtained by Zhao *et al.*[7] and Dou *et al.*[8] The data shown by Zhao *et al.* showed noise in the magnetization at low T and H. They called it dense and very small flux jumps (DSFJ's); it is worth mentioning that this noise in magnetization is different from the flux jumps originating from the *quantum jumps* as argued by Zhao *et al.* They interpreted their findings on the basis of thermomagnetic instabilities where moving vortices in the superconductor may produce a local heating effect, thus aiding more vortices to appear. Recently conducted magneto-optic (MO) studies on laser ablated MgB_2 films showed a very spectacular formation of vortices,[6] however, these observations are not in accordance with the predictions of the critical state model. These MO images are similar to what has been observed in Nb-Al_2O_3-Nb junctions by Durán *et al.*[14] Their images showed that the flux enters in the form of dendrites, and even surprising is the observation that within dendrites there are regions in which sizable numbers of antivortices (the vortex with the inverse field) are nucleated. We believe that the magnetization loops showing DSFJ's, the MO images, and our results of magnetization noise have the same origin, as all these anomalies lie at the same region of the H-T plane. However, the interpretation of DSFJ's given by Zhao *et al.* may not seem very likely, as the region of anomaly is at low temperature where thermal effects are low and disappear completely above 10 K, the region where the thermal effects should become more enhanced. Moreover, the thermomagnetic instability strongly depends upon the rate of field change, i.e., dH/dt, whereas in the magnetic relaxation studies reported here, the magnetic field was held constant throughout the measurement. The interpretation we propose is conceived by the magneto-optic images. At low fields, while the vortex density is still very low and, therefore, the intervortex interaction is minimal there is the possibility that the vortex lattice may melt (reentrant vortex melting).[15] This state will, however, be highly unstable and fluctuations in the vortex lattice or vortex density may lead to the observed noise. A definite boundary in the H-T plane,[7] also indicates a possible phase transition in these materials. It has been pointed out recently that in MgB_2 superconductors the role of surface barriers is minimum; this may be seen by the symmetry of the $M(H)$ loop as discussed in Ref. 7. Thus the dominant pinning mechanism in MgB_2 superconductors seems to be the bulk pinning and if the lattice is already in the melt state as suggested by the MO images then the vortices face little or no resistance in coming in or going out of the sample and thus are responsible for the observed noise in the vortex density or magnetization.

There are, however, other possible explanations: It is well known that the vortex-antivortex pair forming a bound pair at low T and H may dissociate while increasing the temperature (or magnetic field), thus forming a highly unstable vortex state that might be responsible for the observed noise. Such a transition known as Kosterlitz-Thouless (KT) transition has been previously predicted[16] to occur in paired topological defects (vortices in this case), whose interaction energy exhibits a logarithmic dependence on separation. Recently, numerical simulations have been conducted and a new mechanism of flux fragmentation has been proposed that results from the generic distribution of magnetization currents in the critical state.[17] However, even this model does not offer any explanation for the superfast dendrite formation.

In conclusion we have studied the magnetic relaxation effects in MgB_2 powdered samples. Our results indicate a highly unstable vortex pattern at low field and temperature leading to magnetization noise while measuring $m(t)$; the origin of this magnetic noise is still not clear. Some possible explanations have been discussed.

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