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Magnetic Aging

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MAGNETIC AGING

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ABSTRACT

Thermally activated magnetization reversal is of great importance in areas such as permanent magnetism and magnetic recording. In spite of many decades of scientific research, the phenomenon of slow magnetization dynamics has remained partially controversial. It is now well-established that the main mechanism is thermally activated magnetization reversal, as contrasted to eddy currents and structural aging, but the identification of the involved energy barriers remains a challenge for many systems. Thermally activated slow magnetization processes proceed over energy barriers whose structure is determined by the micromagnetic free energy. This restricts the range of physically meaningful energy barriers. An analysis of the underlying micromagnetic free energy yields power-law dependences with exponents of 3/2 or 2 for physically reasonable models, in contrast to arbitrary exponents m and to $1/H$-type laws.

INTRODUCTION

Magnetic properties such as the remanent magnetization are weakly time-dependent. Depending on the context, this degradation is known as magnetic aging or magnetic viscosity [1-3]. For example, permanent magnets loose a small fraction of their remanence each decade [4], and the long-term stability of stored information is a major concern in ultrahigh-density magnetic recording media. Typical relaxation or equilibration times vary between less than a second in superparamagnetic particles and millions of years in magnetic rocks. Similar time-dependent magnetization processes are important soft magnets, although the involved time scales are often in milli- or nanosecond ranges.

Initially, magnetic aging was believed to reflect mechanisms such as eddy currents, but soon it became clear that eddy-current contributions are usually negligible. Some magnetization changes are due to structural aging, but most mechanisms reflect the ther-

Figure 1. Systems where magnetic aging is important.

mal activation over magnetic energy barriers [1]. Unlike structural aging, magnetic aging is reversible, so that the application of a large positive magnetic field re-establishes the original magnetization state. A key question is the physical nature of the involved energy barriers E_a over which thermal activation occurs. Various partially exclusive field-dependences $E_a(H)$ have been proposed, and there is a continuing debate about the applicability of these expressions [5-7].

STRUCTURAL EFFECTS

There are two main types of magnetic aging, namely structural aging and thermally activated magnetization processes. Structural aging refers to both the crystal structure and to defects. Time-dependent structural changes are important, for example, in metastable intermetallics such as $Sm_2Fe_{17}N_3$ permanent magnets, where the decay into SmN and Fe limits the maximum application temperature. However, the magnetism related to the decay is relatively uninteresting, as compared to the anisotropy and Curie-temperature enhancement in the material [8].

A mechanism involving both structural and magnetic degrees of freedom is the Snoek aftereffect in pinning-type magnets. It occurs in steels and related materials and means that magnetic domain walls interact with diffusing carbon atoms. The *static* coercivity of pinning-type magnets is the reverse field necessary to overcome the pinning energy barrier, as indicated in Fig. 2(a). The Snoek effect, Fig. 2(b), means that the energy barrier is reduced by the diffusion of interstitial carbon or nitrogen atoms.

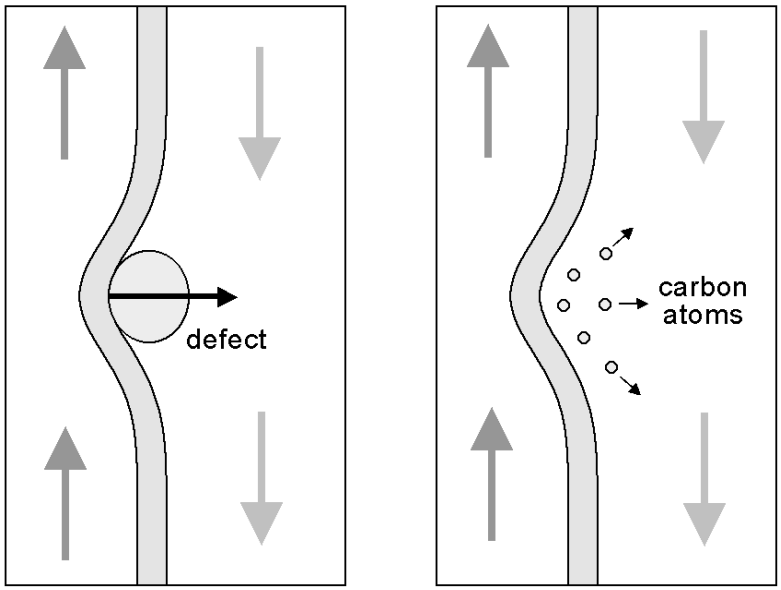

Figure 2. Magnetic aging and domain-wall motion: (a) ordinary structural defects and (b) Snoek effect.

THERMALLY ACTIVATED MAGNETIZATION REVERSAL

Figure 3 compares thermally activated magnetization reversal with the so-called 'static' magnetization reversal, where the micromagnetic energy barriers Ea are overcome due to a reverse magnetic field. The relaxation time obeys so-called Néel-Brown law

$$\tau = \tau_o \exp\left(\frac{E_a}{k_B T}\right) \tag{1}$$

which goes back to the early decades of the 20th century [1]. Here τ is the relaxation time and $\tau_o = 1/\Gamma_o$ is an inverse attempt frequency of order 10^{-10} s. Depending on the context, Eq. (1) is also known as the Néel or Néel-Brown relaxation law.

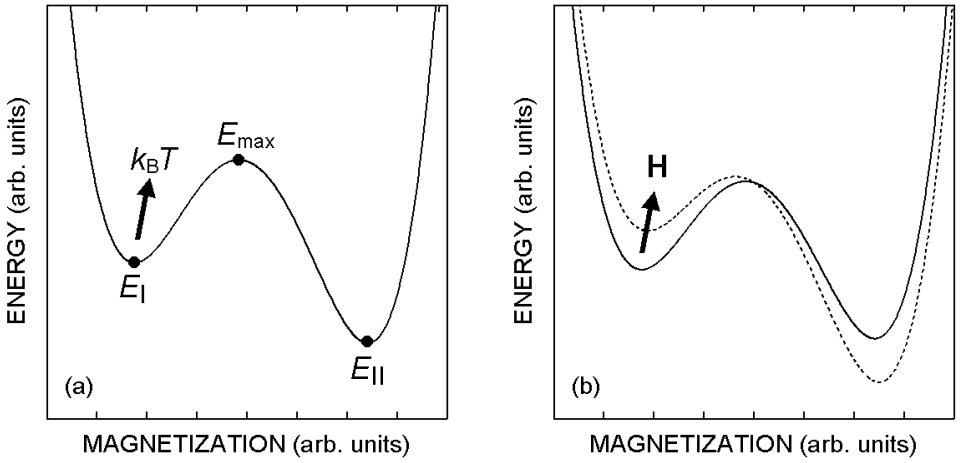

Fig. 3. Thermally activated magnetization reversal (left) and static coercivity (right).

Typically, thermal activation is a small correction to the leading field-dependence $E_a(H)$. Inverting Eq. (1) yields the energy barriers $E_a = k_B T \ln(\tau/\tau_o)$ that are thermally accessible after some time τ. Taking $\tau = 100$ s, we reproduce the famous result $E_a \approx 25\ k_B T$. At room temperature, this corresponds to a temperature equivalent of about 7'500 K. However, energy barriers often exceed 100'000 K [3, 6], so that some supporting external field is necessary to reduce them to $25\ k_B T$ before thermal activation takes over.

Power Laws with m = 3/2 and m = 2

The starting point of the description of thermally activated magnetization reversal is the micromagnetic (free) energy $F(\mathbf{M}(\mathbf{r}), K_1(\mathbf{r}), A(\mathbf{r}))$, where $\mathbf{M}$, K_1 and A are the local magnetization, anisotropy, and exchange stiffness, respectively. Figure 3 is an example of a micromagnetic free energy, although only one degree of freedom, namely the relevant reversal mode, is shown in the figure. Series expansion of the micromagnetic free energy yields [6]

$$E_a \sim (H_o - H)^m \tag{2}$$

where H_o is the static coercivity and the exponent m = 3/2 or m = 2 depends on the symmetry of the magnet [5, 6, 9]. Most systems have m = 3/2, but m = 2 for highly symmetric systems, such as aligned Stoner-Wohlfarth particles.

There have been approaches to treat m as an adjustable or field-dependent parameter, and it has been has argued that m implies some kind of averaging over energy barriers. Other proposed dependences are m = 1 laws and relations such as $1/H$ and $1/H - 1/H_o$ [7, 10]. The discussion has been fueled by the popular belief that the exponents m = 2 and m = 3/2 are limited to specialized or highly simplified models. In fact, they go far beyond the Stoner-Wohlfarth approach [5] and describe a broad range of coherent and incoherent magnetization processes [6]. It has also been possible to derive the m = 2 and m = 3/2 modes from realistic energy landscapes F. Other modes involve very crude approximations, are incompatible with the real structure of the magnets, or misinterpret the physics of the magnetization reversal. For example, the $1/H$ law corresponds to the physically unreasonable prediction of an infinite zero-temperature coercivity, whereas the $1/H - 1/H_o$ dependence reduces, by series expansion, to m = 1.

Linear laws, m = 1, are used in simplified models and to evaluate experimental data in terms of activation volumes V^*. However, so far it has not been possible to derive them from physically reasonable energy landscapes [6], and V^* is not necessarily equal to the physical switching volume V [4]. Figure 4 shows a fictitious pinning energy landscape that would yield a linear law. In reality, the singularities responsible for the (piecewise) linear nature of $E_a(H)$ are smoothed by the continuous domain-wall profile. The smoothing affects just a few nanometers, but the corresponding energies are typically larger than 25 k_BT.

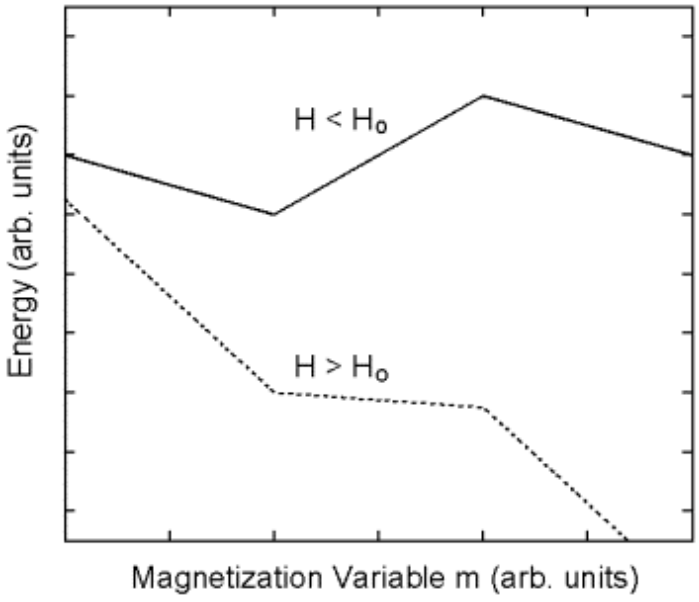

Fig. 4. Example of a fictitious energy landscape with m = 1.

Effect of Real Structure

Thermally excited modes are supported by real-structure features and correspond to static reversal modes. There is no justification for using arbitrary magnetization modes to fit experimental data. Such modes have often energies of the order of $\delta_B^3 K_1 \sim 100\,000$ K, as contrasted to the accessible range of 25 $k_B T$ [11]. Figure 5 shows some examples of physically meaningful (a) and physically unrealistic modes (b-c). Spin configurations such as Fig. 5(b) and (c) are limited to though frequently occur in *imperfect* magnets. The inhomogenity or randomness yields a renormalization of the zero-field energy and of H_o, but leaves the functional structure of Eq. (2) unchanged.

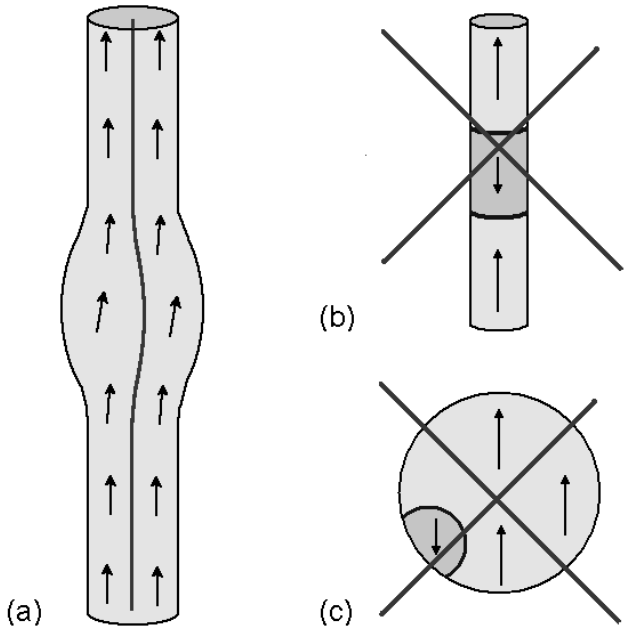

Figure 5. Physically meaningful (a) and arbitrary (b-c) magnetization modes. Note that (b) and (c) refer to homogeneous ellipsoids of revolution; defects drastically change the model predictions.

An exception is very small or 'superparamagnetic' particles, where $E_a \sim 25\ k_B T$ at room temperature [12]. This limit requires the inclusion of higher-order terms in Eq. (2), and there are corrections to the simple $m = 3/2$ and $m = 2$ power laws. However, even in this case, $E_a(H)$ derives from the micromagnetic free energy and must reproduce Eq. (2) in the limit of low temperatures. Otherwise, $E_a(H)$ acquires the character of a pheno-menological fitting function that describes a relatively narrow energy or temperature window.

CONCLUSIONS

In summary, we have investigated the physical origin of magnetic aging. Emphasis has been on the energy barriers responsible for thermally activated magnetization

reversal. To obtain meaningful expressions for the relaxation time, it is necessary to start from physically reasonable energy landscapes, based on the microstructure of the magnet. Neglecting superparamagnetic effects, the energy barriers responsible for thermally activated slow magnetization dynamics are of the power-law type, with exponents m = 3/2 or 2, depending on the symmetry of the problem. In contrast to widespread belief, these laws are not restricted to Stoner-Wohlfarth particles, but describe a broad range of pinning and nucleation mechanisms. Arbitrary exponents m and $1/H$-type energy-barrier dependences are not supported by the real structure of the magnets and yield physically unreasonable predictions, such as infinite zero-temperature coercivities.

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