

Introduction

Macroscopic magnetic systems are intractable, at the present time, by rigorous approaches: strong approximations are usually needed. The reason lies in the competition between the different energy terms contributing to the energy of the magnetic material examined. There are energy terms – exchange, interaction with the external field – that are minimised in the conditions of maximum order, that is when the elementary magnetic moments are all parallel to each other. Other energy terms – anisotropy, magnetostatic energy – reflect the conditions of local disorder of the material, both short and long range. Then, there are energy terms – demagnetising energy – that favour the conditions of minimum magnetic moment over the system volume. Although the origin of the demagnetising energy is magnetostatic, it is customary to consider it separately as it depends on the shape of the body. Its main consequence is the origin of the shape anisotropy: a preferential direction for the magnetization that depends on the form of the object being magnetized.

The competition of the energy terms here summarised is reflected in the energy minimization. Being the relevant spatial scales very different for the different terms (as an example, the sample dimension scale for shape anisotropy, the Angstrom scale for the exchange energy) the system self-organizes itself with different structures at different scales. Let us take, for example, a nanocrystallized amorphous ribbon, under a longitudinal external field. On length scales of the order of the sample dimension we will observe a small number of longitudinal, regular domains. In a non amorphous material the presence of few, parallel domains could be due to the anisotropy energy. In our case instead this structure will result from the attempt to decrease the demagnetizing energy, whose main contribution comes from the free magnetic poles (regions where $\nabla \cdot \mathbf{M} \neq 0$) at the ribbon edges. The presence of outgoing and ingoing flux lines from neighbouring domains leads the magnetic flux to close in a small region. Being the magnetostatic energy given by the integral of the square of the magnetostatic field over all space, if the flux lines remain confined in a small space volume the magnetostatic term abruptly decreases. This effect is obtained with numerous parallel domains with opposite magnetization. To further minimize the demagnetizing energy, at length scales just smaller we will observe closure domains at the edges of the sample. With the aid of 90° domain walls the free magnetic poles can be theoretically completely eliminated. Observing the material at the length scale of its defects, we will observe, right around the defects, small closure domains that minimize the magnetostatic energy (the length scale at which we are now is not clearly defined, as the defect dimensions follow a power law on a great range [Ferrara 1997]). At last, descending to the length scale of the crystallized grains, it is possible to see that, if their dimension is lesser than the width of a domain wall, they are monodomain structures, where the exchange energy dominates, and all magnetic moments are aligned. We conclude then that the choice of the length scale on which a model will be defined will be indicative of the approximations introduced.

Once a model of the system is available, for example as an Hamiltonian, the non trivial problem of its solution remains. Its solution consists in the extraction from the Hamiltonian of the thermal averages of the physical quantities one is interested in. A possible approach to this problem is the so-called Monte Carlo method. It is a methodology that permits one to obtain an estimate of the physical properties of the system at the thermodynamic equilibrium. This is obtained without having to know all the possible states of the system in the configuration space, but sampling among them a certain, much smaller, number, in a random manner. The sampling is performed taking with higher frequency the system states that in a major way contribute to the energy, and occasionally even states with higher energy. The success of this method is due to the conjugation of two elements. From one side the physical element of a natural trend of the system to move towards states with minimum energy. From the other side, the possibility for the system to ascend to temporarily to greater energy states: this behaviour allows the system not to be trapped in local energy minima, but to explore in a more complete way the configuration space.

One of the models that use as a starting point the energy of the system and study its minimization, to know the set of the stable system states, is known as micromagnetics. If it was possible to find the direction of the

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magnetization that, at every point in space, minimizes the energy, the result would allow to know automatically the domain structure of the body. This approach leads to useful results in small particle materials. The solution of the problem that micromagnetics presents is usually expressed by Brown's equations. These equations define an effective field inside the body, responsible for the magnetization process, and an equilibrium condition, that basically requests that, at every point, the local magnetization follows the direction of the effective field. The effective field is a superposition of fields with different origin: the external field, and the fields due to the magnetostatic effects, to the magnetoelasticity, to the anisotropy, and to the exchange interaction. This decomposition follows exactly the decomposition of the energy, that consists of an external field energy, magnetostatic energy, magnetoelastic energy, anisotropy energy, and an exchange energy.

In this work we studied the magnetization dynamics in a variety of materials, both metallic and non-metallic, trying to gain some insight into the energetic aspects of the phenomena involved. The metallic materials studied are amorphous and polycrystalline ribbons. In this field we concentrated more on the Barkhausen effect, an interesting signature of the underlying energetic properties of the material. The non-metallic materials studied were garnet films, examined both from the viewpoint of their hysteretic properties, and of their domain structure. This material has been chosen precisely for its interesting feature of revealing clearly its whole domain structure by visual inspection with Faraday effect. To be able to assign a meaning to our observations, two models have been considered. The ABBM model, a simple one-dimensional model of domain wall moving in a random energy landscape, has been useful to understand some key features of our Barkhausen and hysteresis measurements. The RFIM model, an Ising model with an additional random field at every spin location, helped us to better understand the onset of a complex energy landscape, with a small number of given parameters. Both the models share the property of a very small number of degrees of freedom, nevertheless they demonstrate a great complexity when explored in detail.

Energy Terms

In the calculation of the energy of the material, in a given configuration, the terms that we have to know are: the exchange term E_X ; the magnetostatic term E_M ; the anisotropy term E_K ; the external field interaction term E_H ; the magnetoelastic term E_S . The energy is given from:

$$E = E_X + E_M + E_K + E_S + E_H \quad [1]$$

Knowledge of the energy is fundamental in the calculation of the most probable states in which the system will be. Let us consider the terms that compose [Eq.1] one by one.

Exchange Energy

We can discuss the exchange energy analyzing a system composed of a great number of atoms. The exchange energy, first investigated by Heisenberg, has quantum-mechanical origin and acts between the spin of the electrons of neighbouring atoms, forcing them to be, in ferromagnetic materials, parallel:

$$E_{XX} = -2J \sum_{i>j} s_i \cdot s_j \quad [2]$$

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where $J > 0$ is the exchange constant. It is clearly visible as the minimum energy value for each couple is attained when \vec{s}_i is parallel to \vec{s}_j . Although the exchange interaction is short range, allowing thus to truncate the sum to nearest neighbours without a great error, this sum for a real material is of course not possible, unless one is using a computer model with a reasonable number of spins. Instead, it is possible to express the value of E_{EX} with the approximation of the *molecular field*. This estimate goes back to the work of Weiss on ferromagnetism, when he discovered that the atomic magnetic moments interact so strongly that they couple with each other with an energy whose order of magnitude is greater than the energy of the thermal bath at room temperature. Under this hypothesis, the magnetic moments behave as if they were in a field given by the sum of the external field and the molecular field H_W , proportional to the average magnetization, $H_W = N_W M$. This proportionality holds because it is produced by the surrounding magnetic moments. In this approximation, the energy of the system due to the molecular field is:

$$E_{EX} = -\frac{1}{2} \int_V dV \mu_0 N_W M^2 \quad [3]$$

where ΔV is the volume considered, and the constant N_W is proportional to the Curie temperature. From [Eq.3] one can see that the minimization of the exchange energy – at $T=0$ – brings the system in a state of parallel spins, with total magnetization $|\mathbf{M}| = M_s$ (where M_s is the saturation magnetization: $M_s = N m$, being m the elementary magnetic moment and N the number of moments per unit volume) anyway, no constraint at all is put on the direction of \mathbf{M} .

When other energy terms are considered, we observe two additional effects: some constraint on the direction of \mathbf{M} is possible (anisotropy), so that axes of easier magnetization can be defined; and other energy terms are in competition with the exchange energy, both on the system as a whole and locally. The consequence is the partition of the system in domains with different orientation of the magnetization.

Magnetostatic Energy

The magnetostatic energy is strongly dependent on the shape of the magnetic body. This is due to the fact that it originates from the contribution of all the regions where $\nabla \cdot \mathbf{M} \neq 0$ [Cullity 1972], and these regions usually can be found at the surface of the body. Moreover, the divergence of the magnetization can be different from zero inside of the body, when it is not uniformly magnetized.

The magnetostatic energy, in principle, can be connected to the work spent to build the magnetic object, bringing in situ the single elementary magnetic moments, from an infinitely distant position. Let us consider two elementary magnetic moments, side by side. From the point of view of the closure of the magnetic flux, the antiparallel configuration is more stable than the parallel configuration. From this elementary example we see that the magnetostatic energy is usually in competition with the exchange energy, and it is necessary to start from this competition to find the more stable configurations.

A good starting point is the division of the magnetic body in a great number of elementary volumes ΔV . We will see in the sections devoted to the quantitative measurements on the magnetic state of a body starting from its photographic images (Faraday effect, Kerr effect, Scanning Electron Microscopy) that we will perform something similar, taking a single pixel as a uniformly magnetized object. We suppose that our elementary

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volume ΔV be composed from a great number of elementary magnetic moments \mathbf{m}_i whose distribution inside the volume is supposed random. The number of moments is so great that an average moment density \mathbf{M}_i can be considered. If each elementary moment \mathbf{m}_i generates a magnetic field \mathbf{B}_i , then the potential energy of a single moment \mathbf{m}_0 is given from $-\mathbf{m}_0 \cdot \sum_i \mathbf{B}_i$. The magnetostatic energy of the body as a whole is then

obtained with the successive steps of averaging the moments inside ΔV ; correcting the result to exclude the possibility of two moments occupying the same place; at last, summing over the volumes ΔV composing the body. We then obtain:

$$E_M = -\frac{\mu_0}{2} \int_V dV \mathbf{H}_M \cdot \mathbf{M} \quad [4]$$

where \mathbf{M} is the magnetization, \mathbf{H}_M the magnetostatic field created by the body: $\mathbf{B}_M = \mu_0(\mathbf{H}_M + \mathbf{M})$. In the simple cases where the relationship between \mathbf{H}_M and \mathbf{M} is linear $\mathbf{H}_M = -N \mathbf{M}$, where N is the demagnetizing factor, [Eq.4] becomes

$$E_M = \frac{\mu_0 N}{2} \int_V dV M^2 \quad [5]$$

showing the relationship between magnetization and magnetostatic energy.

Anisotropy Energy

Anisotropy energy is, literally, every kind of energetic term that privileges particular directions for the magnetization. The energy surface, at a given point in a magnetic body, can present different minima at different possible orientation of the magnetization. The directions corresponding to these minima are called *easy axes*. The consequence of a so vague definition is that under this category it is possible to find the magnetocrystalline anisotropy, the shape anisotropy, the stress anisotropy, among the others. The only term we are interested here is the magnetocrystalline anisotropy, because the shape anisotropy pertains to the magnetostatic energy, while the stress anisotropy pertains to the magnetoelastic energy.

The origin of the magnetocrystalline anisotropy lies in the spin-orbit coupling. The crystalline lattice reflects a certain set of directions (crystalline axes), and the orbital angular momentum of the electron \mathbf{L} follows these directions under the action of the potential energy given from the crystalline field. At the same time, an energetic contribution (spin-orbit coupling) ties \mathbf{L} and the spin of the electron \mathbf{S} with a factor proportional to $\mathbf{L} \cdot \mathbf{S}$. If there is an angle θ between the external field \mathbf{H} and the crystalline axis, we have an unstable state. If the spin-orbit energy dominates on the energy due to the crystalline field, \mathbf{L} rotates to be parallel to \mathbf{S} and to \mathbf{H} . If the contrary is true, \mathbf{S} rotates to be parallel to \mathbf{L} , forming an angle θ with \mathbf{H} . In both the cases, we observe an increase in the energy, due to the potential energy of the interaction of \mathbf{L} with the crystalline field, or to the interaction energy of \mathbf{S} with \mathbf{H} .

Different kind of anisotropies can be found in crystals. Two classical cases are: the uniaxial anisotropy, and the cubic anisotropy. In the uniaxial case, if θ is the angle between the easy direction and the magnetization direction, the anisotropy energy can be expressed as $E_x = \int_V dV [K_0 + K_1 \sin^2 \theta + K_2 \sin^4 \theta + \dots]$, but usually the formula is used just to the second power, and the constant K_0 is neglected:

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$$E_K = \int_V dV K_u \sin^2 \theta \quad [6]$$

where we used the more commonly used syntax of K_u for the uniaxial case. We see that the energy has two minima for the $\theta = 0, \theta = 180$ directions, if $K_u > 0$ (easy axis anisotropy); if $K_u < 0$ instead, any direction perpendicular to the z axis is allowed (easy plane anisotropy).

In the cubic case, the director cosines $\alpha_1, \alpha_2, \alpha_3$ of the angles between the magnetization and the easy axes are used. The energy is:

$$E_K = \int_V dV K_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_1^2 \alpha_3^2) \quad [7]$$

stopping at the first non constant term, as we've done in [Eq.6]. In this case we have two possible sets of easy directions: if $K_1 > 0$, the easy direction is $\langle 100 \rangle$, being $\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_1^2 \alpha_3^2 = 0$ the case when E_K is at a minimum. On the contrary, when $K_1 < 0$, the easy direction is $\langle 111 \rangle$, because the minimum of E_K is for $\max(\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_1^2 \alpha_3^2)$.

Magnetoelastic Energy

Magnetoelasticity should be considered according to two complementary points of view: magnetostriction, or the deformation of the crystal lattice consequent to a particular magnetic state. And the stress anisotropy, that is the presence of easy axes as a consequence of stresses applied to the material. The magnetostriction is an important factor to be considered when studying the domain structure of a body: for example when studying the closure domains in a cubic material, we see that the competition of deformations along the 90° walls is alone sufficient to make energetically unfavourable to have few, big closure domains, in contrast with a structure with many small closure domains. The energetic term to be considered when in presence of applied stresses is dependent on the director cosines $\alpha_1, \alpha_2, \alpha_3$ of the magnetization, and on the director cosines $\beta_1, \beta_2, \beta_3$, of the applied stress σ . On a cubic crystal:

$$E_S = \int_V dV \left[\frac{3}{2} \lambda_{100} \sigma (\alpha_1^2 \beta_1^2 + \alpha_2^2 \beta_2^2 + \alpha_3^2 \beta_3^2) + 3 \lambda_{111} \sigma (\alpha_1 \alpha_2 \beta_1 \beta_2 + \alpha_2 \alpha_3 \beta_2 \beta_3 + \alpha_3 \alpha_1 \beta_3 \beta_1) \right] \quad [8]$$

an applied stress along the direction β will generate an uniaxial anisotropy, easy axis or easy plane depending on the signs of $\lambda_{100}, \lambda_{111}, \sigma$.

Field Interaction energy

This energetic term reflects the coupling of the system with the external world. If we have an applied field \mathbf{H} , the magnetization \mathbf{I} has a magnetic field energy of

$$E_H = - \int_V dV \mathbf{I} \cdot \mathbf{H} \quad [9]$$

and will be at a minimum when the system magnetization is parallel to the external applied field. This energetic term acts as the main driving force that operates on the magnetic system.

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State of the system in the energy landscape

The energy [Eq.1] is a function of many terms, among which: the variables describing the state of the system on the energy landscape (we will discuss them later on), and the external forces (applied stresses, external field). The last ones are not necessarily constant during time. In fact, it is usually interesting to study the evolution of the system state with varying external field.

A possible way to visualise this complex function is to just consider the multi dimensional energy landscape as a function of the state variables, and to study the change of the state of the system on this landscape, due to the external energy terms. This corresponds to the study of the energy only. In this case, the energy landscape is fixed in time, and the external forces act on the system state, moving it. A different approach is the Gibbs energy study, where, having taken into account all the terms, including the time dependent ones, the energy landscape changes in time. The system state changes too, not as a consequence of the action of external forces, but just as a consequence of the principle that the energy of the system must be at a minimum.

Now it is important to obtain some insight into the possible ways to describe the system state. The system state is the minimum set of variables that allow us to know where the system is found on the energy landscape. An approximation would be to consider the magnetization as describing the state of the system. This point of view, that probably originates from the picture of the typical hysteresis plane, where the response of the system \mathbf{I} is plotted against the force acting on the system \mathbf{H} , is not exact. It is important to observe that many magnetic states are possible, with the same magnetization. The magnetization is a state function, but it is degenerate. This can be observed better, as we will see, in the Ising spin systems. In these systems, composed of a number N of spins S_i that can have the values $+1$ or -1 , the magnetization is calculated simply as $I = \sum_{i=1}^N S_i$, and obviously many configurations lead to the same I value. Instead, the state

of the system is unambiguously defined when giving the configuration $\{S_i\}$. In real systems this corresponds to the function $\mathbf{m}(\mathbf{x},t)$ describing the local magnetization of the body during time. Although in real systems the exact definition of the state of the system is, of course, impossible, there are some possible approximations. A particularly fruitful one is the division of the material in magnetic domains. Hence, it is possible to consider every magnetic moment inside a domain as being oriented exactly in the direction of the average magnetization of the domain. Thus we are able to study the state of the system at a higher level, by observing the shape and dimension of the domains. This level is usually attainable from our measurement systems, for many different materials. The details of this approach are discussed in the sections devoted to the study of the garnet films (§5). It is of course an approximation, having neglected all the local deviations of magnetization orientation inside a domain, as well as the details on the position and orientation of the magnetic moments forming the domain walls. Another possibility, as we said, is the study of abstract systems like the Ising spin systems. It is a very interesting case, from this point of view, because at every moment the state of the system $\{S_i\}$ is exactly known. The drawback in this case is that the computer simulations are extremely heavy, so that we are really far from simulating systems with a number N of spins sufficient for comparisons with real systems.

From now on, let us suppose that the state of the system is exactly known. Can we guess from the magnetic behaviour some basic property of the energy landscape, or, conversely, can we induce some magnetic property of the system, from some hypothesis on the energy profile?

Complex energy landscapes

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The energy of the system possesses some long range properties, due for example to the sample shape (magnetostatic term). These properties control the overall shape of the energy landscape. For example, the magnetostatic term in a one-degree-of-freedom model, with one domain wall moving along an infinite metallic slab, is proportional to x^2 , where x is the wall position: this originates the typical parabolic energy shape. Some features are instead short range, and are due to the interactions of the domain walls with the defects of the medium, or with other domain walls. Experimentally, we observe that in many ferromagnetic materials both the phenomena act as dominant terms, while in garnet films the first one is usually negligible. In the garnet films the defects are important just at the nucleation stage, when the first stripe domains get nucleated: it happens at the main material defects, or at the sample edges. But the successive magnetization processes involve domain wall motion that is just hindered by the interaction with other domain walls: these materials are usually defect-free.

The presence of disorder means that to describe the system we need a huge number of variables, for example the local magnetization \mathbf{m}_i in every elementary volume ΔV_i in which we divide the system. The disorder, moreover, implies an additional feature: the energy landscape becomes very complex [Stein 1987], where with *complex* we mean that there is a great number of local minima where the system can be considered stable. For this reason the question about the nature and properties of the demagnetized state, i.e. the global minimum, is very hard to tackle.

The short range features of the energy can be seen as noise overimposed on the overall energy profile. They can appear as series of small energy wells with decreasing energy barriers, one nested inside the other. Being usually described with stochastic processes, we have to derive their properties with statistical instruments, e.g. the Fokker-Planck equation (§3). The important fact here, is that the fine structure of the energy landscape, that is originated from the disorder, generates usually a huge number of locally stable states, separated by unstable regions. As the system state changes, due to external forces, the usual stability rules are followed: minima $\nabla E=0$; $\nabla^2 E>0$ are stable states; states in which $|\nabla E|<0$ are unstable states, and when the system is in these regions moves itself even in the lack of external forces, under the path on which $|\nabla E|=max$; states in which $\nabla E=0$; $\nabla^2 E<0$ are unstable states, and small fluctuations, thermal or of the external force, will be able to drive the system away from its current state.

It is important to add a consideration to this brief presentation. In whichever state the system can be, there will always be thermal fluctuations, their intensity decreasing with T . Thermal fluctuations allow us to explore different regions of the energy landscape [Stein 1987]: the size of the region explored depends both on the temperature and on the experiment timescale. By waiting a time long enough, the system will be able to exit from any energy well. Of course, the time required to overcome the energy barrier will be proportional to the depth of the energy well. Waiting a very long time, then, we expect that the energy of the system will decrease, until, hypothetically, it will arrive at the demagnetized state, where the energy is at its minimum.

We saw that a huge number of energy minima is usually present. A useful tool used in these cases is that of fractal mathematics. The use of the fractal analysis is supported by many instrumental observations (§4): even just the visual observation of the Barkhausen jumps during the magnetization process shows immediately the typical fractal hierarchy of smaller and smaller structures nested inside each other, revealing finer and finer details as the sampling increases. But, as any fractal structure found in nature, even in this case there must be both an inner and an outer threshold. The inner threshold should correspond to the maximum magnetization increase possible without originating an irreversible jump. The outer threshold corresponds to the greater Barkhausen jump possible in the sample, and this is of course limited by the dimensions of the sample to $2 I_s V$, where V is the sample volume. These considerations are important, because if the fractal details present in the energy had no inner threshold, it would be impossible to have any reversible movement of the domain walls: at any position the wall would be in an unstable position, ready to generate a Barkhausen jump. If instead an inner threshold is present, both the reversible movement for small domain wall displacements and the irreversible movement (Barkhausen jump) for larger domain wall displacements are present.

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To follow the movement of the energy state along the energy landscape in detail it is of course usually impossible, but we can learn something about the basic aspects of the problem from the following simple model. Let us consider a simple system with just one degree of freedom x , playing the role of the position of a domain wall. As x increases or decreases, under the action of an external field H , accordingly the magnetization will change. The variables x and H are conjugate.

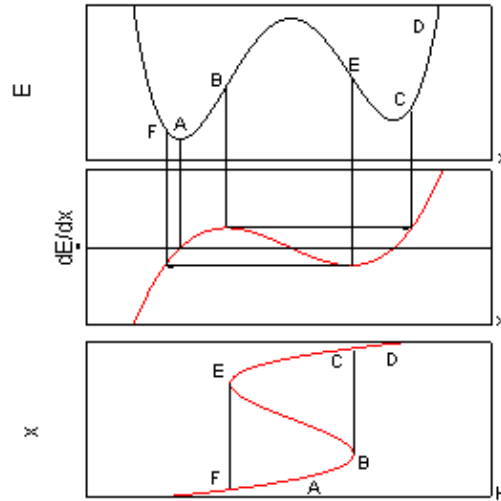


Fig.1 Elementary hysteresis loop deduced from the energy profile

Now, different hysteretic behaviours are possible, depending on the shape of the energy landscape that the system is seeing. If we consider a simple two-wells energy profile (Fig.1 and [Cullity 1972]) we can easily follow the movement of the state of the system (identified with the x coordinate) under the action of the external field, that we suppose varying very slowly (we neglect, for now, the discussion concerning the quantitative meaning of *very slowly*). The system state changes from A to B in a reversible way. At point B the system state will change irreversibly to C , characterized with $\left. \frac{dE}{dx} \right|_B = \left. \frac{dE}{dx} \right|_C$. Any attempt to go back to the

$A-B$ branch will lead us to pass through another branch, i.e. to follow the path $C-E-F$. The energy loss during a cycle can be obtained from:

$$W = \oint H dx \quad [10]$$

This simple case illustrates easily as the two-well (and, more generally, the many wells) picture lies at the origin of hysteresis. It must be stressed that any state along the curve $A-B$, and $D-E$ is a well defined state from the thermodynamic point of view. The state is defined with the current domain wall position x . The movement along these branches is completely reversible; the vertical Barkhausen Jumps $B-C$ and $E-F$, instead, are *irreversible* jumps, and the system state is not defined in between.

Thinking about the energy landscape as a whole, there are some limit cases that could be assumed; we can discuss them using the simple model just described. If the system possesses just two minima, as shown in Fig.2:

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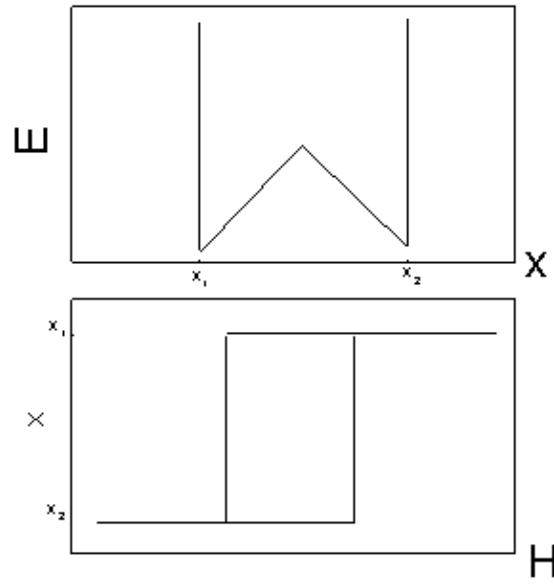
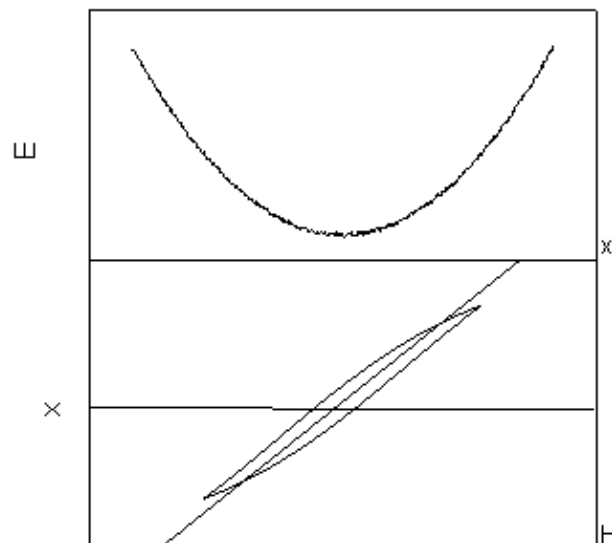


Fig.2 Two wells energy landscape

The energy profile is undefined outside the region $x_1 < x < x_2$, to obtain saturation. What we have here is a system whose magnetic behaviour presents just two Barkhausen jumps, during which we have the total reversal of the magnetization. There is no stable state apart from x_1, x_2 .

The opposite limit case is that in which we have an energy landscape with a huge number of minima, with a given distribution of depths, overimposed on the parabolic energy well, as we discussed before:



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Fig.3 Fully random energy landscape

As shown in Fig.3, the hysteresis loop has an average slope, direct consequence of the derivative of the parabolic well. The Barkhausen jumps are present, but are not visible, being their size much smaller than the total domain wall displacement. We can observe that at the reversal points the magnetization does not immediately follow the mean slope. This phenomenon (see also [Neel 1942, 1943]) depends on the statistical characteristics of the noise present.

A notable feature of this case is that, due to the presence of a so great number of minima, the stable states can be found for any domain wall position x .

From the comparison between these two cases, it is interesting to observe that they are opposite even in the context of the energy loss W : it is higher in the first case, lower in the second case. Actually, in the second case it can be obtained from the average fluctuation of dE/dx : $W \sim \sigma_{dE/dx} \cdot \Delta x$, where Δx is the total domain wall displacement during the hysteresis loop.

A final consideration on another effect due to disorder concerns the possible presence in the magnetization process of the self-organized criticality. With this name is represented the property of a whole class of dynamical systems [Grinstein, Lee 1990]. Two main attributes are common to these systems. They exhibit generic scale invariance, that is, the correlations decay only algebraically both in space and time. And the scale invariance is obtained very easily, without tuning any external parameter, contrary to usual critical systems. This behaviour is often described by saying that the system drives itself into the critical state [Miranda, Herrmann 1991]. In some way, the system never attains the lower energy state, nor it is able to tend towards it [Che, Suhl 1990]: it selects instead a class of metastable states, in which some average quantities are conserved, as the average slope in the famous case of the sandpile study [Wiesenfeld, Tang, Bak 1989]. Many studies in the last years [Cote, Meisel 1991; Sethna 1993] have been devoted to the possibility that the magnetization process develops as a self-organizing critical system, where the quantity to be conserved is the average permeability. Whether this can be the case is still an open question, anyway it has been shown [Miranda, Herrmann 1991] that the presence of disorder in a system showing SOC, does not destroy it, however, it can change the size and duration exponents.

Relationship between the magnetic behaviour and the energy landscape shape

It is interesting to observe how the knowledge of the form of the energy [Eq.1] can be sometimes sufficient to give some insight into many magnetic properties of the system.

As an example, if the energy profile of a system could be known, the hysteresis loop shape would be obtained, with a reconstruction similar to that discussed in the preceding chapter. Here, of course, it is important to know exactly what system we are talking about. If the energy is the energy of the whole physical system, then we can calculate the hysteresis loop shape of the whole system. To some extent, this can be measured in garnet films (§5), while, for the random field Ising model (§2), we can have the exact energy calculation. If instead we are talking about a subsystem of the sample, some additional consideration must be done. For example, we could make some prediction about the energy profile that a domain wall "sees" when moving in the sample during the magnetization process (study of the pinning field profile (§3)). In this case the hysteresis loop shape obtained is an elementary loop, and the hysteresis loop of the whole sample will be obtained only when summing these loops over the volume of the sample: this is due to the fact that every domain wall will move under the action of a distinct energy profile.

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Another feature of the magnetization process that can be observed from the point of view of the energy profile, is the Barkhausen effect. As we have shown in the discussion of Fig.1, just with the simple two-wells energy profile appears the feature known as Barkhausen jump, commonly observed in the magnetic measurements. These jumps signal the presence of irreversible changes of the system state, and are considered to be the primary source of hysteresis. The simple squared loop (*hysteron*) which is the basis of the Preisach Model [Bertotti *et al.* 1993], derives from a two-wells energy profile similar to Fig.1, but the energy has constant slope in the four branches that create the two-wells structure. In this way the hysteron is strictly rectangular. In real systems, the Barkhausen noise comes usually from the large number of Barkhausen jumps that occur when the domain walls move in a medium that contains a certain amount of defects. These defects cause the pinning of the walls, that, as a consequence, move along an energy profile composed of a sequence of energy wells of different depth.

An energetic study of the magnetization process could lead some insight even on another magnetic phenomenon, that is the magnetic viscosity, or *aftereffect*. In magnetic materials there are many time dependent phenomena, whose nature really is different from each other. Usually they all are named aftereffect, causing much confusion. The disaccommodation process, for example, refers to an increase in permeability with time, having set the external field to a certain value. The explanation, usually, is that carbon atoms, present in the metal, diffuse along certain preferred directions, so stabilizing the domain walls. From an energetic point of view, this can be described easily. The system is in a stable state at the moment the external field gets fixed, but the energy landscape changes with time: the system being in an energy well, its depth increases slowly with time, so stabilizing even more the state.

Other time dependent effects can be noticed, for example in garnets. A typical, visual, inspection that can be done is obtained when increasing suddenly the external field and fixing it at a certain value. It can be observed a rearrangement of the stripe domain pattern, followed by successive macroscopic rearrangements that can occur even on time spans of 10÷ 100 sec (§5). We infer, qualitatively, that the energy wells in garnets are, apart from being in a huge number, very accessible from each other, so that these materials are very sensible to small thermal fluctuations. These fluctuations slowly drive the system towards the state more stable at the given field, that is towards the anisotropy curve. This study could teach us something about the energetic terms that are dominant in the energy [Eq.1]. It has been shown with computer simulations [Sampaio *et al.* 1996] that if the exchange interactions are dominant on the dipolar interactions the magnetic relaxation follows an exponential decay, while, if the converse is true, the law followed is that of a power law decay.

Overview

In chapter §2 the Random Field Ising Model (RFIM) will be introduced and discussed. This study has been chosen to override the great difficulties involved in the description of real magnetic materials: we found the RFIM a good compromise between the reduction of the number of degrees of freedom, and the complexity still present in the model. This model is a simple evolution of the well known Ising Model, that brings in the Hamiltonian a local random term, thus enabling to investigate its behaviour in the presence of disorder. Both the two and three dimensional cases have been studied. We concentrated at first on the reconstruction of the hysteresis loops. Observing how they reveal qualitatively different internal behaviours, depending on the relationship between the strengths of the exchange interactions and the random fields, we studied the critical behaviour of the system. The last part of our study concerned the possible ways to reach the demagnetized state; an analysis useful to this study has been the survey of the energy landscape explored under varying external field.

In the chapters §3,4 we discuss the ABBM model [Alessandro *et al.* 1990a, 1990b]. It is a single degree of freedom model, that describes the motion of a domain wall in a random medium. Although very simple, it

Introduction

gives very important results, both when applied to the interpretation of experimental data, §4, and also when it is used as a starting point for computer simulations, §3. Among the results showed in §4 we can anticipate that it correctly predicts the Barkhausen jump size and duration distributions, the Barkhausen noise distribution, and the power spectra. In §3 we show that the computer simulations present an hysteretic behaviour that possesses the correct features both at low fields (Rayleigh hysteresis loops) and at high fields (hysteresis loops dominated from the magnetostatic effects). When calculating the losses associated to the loops we both observed and deduced theoretically that the losses separation law is followed.

Chapter §5 is devoted to the project that lead to the construction of an optical bench, to be used to study magnetic garnet films with the Faraday effect. We have been able to acquire optically the hysteresis loops, as well as to acquire images of the samples during the magnetization process. With the knowledge of the hysteresis loop data, it has been possible to start some interesting studies, among which the behaviour of the losses and the coercive field at varying frequencies. Using the images acquired together with some computer programs we wrote, many informations have been extracted concerning the topology of the domain structures, and the variation of the energy of the sample, during the magnetization process.