PYL 102

Wednesday, Oct. 30, 2024

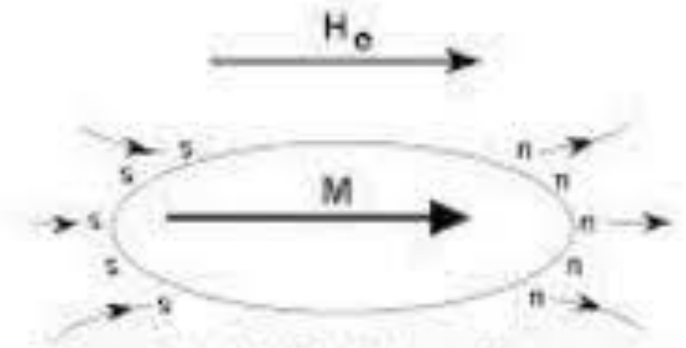
Magnetic anisotropy and domain wall motion

Shape anisotropy

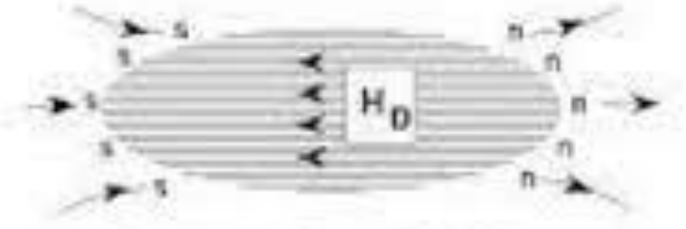
• It is easier to induce a magnetization along a long direction of a non spherical material than along a short direction.
• This is because the demagnetizing field is less in the long direction (induced poles at the surface are farther apart). Thus, a smaller applied field will negate the internal demagnetizing field.
• For a prolate spheroid with major axis **c** greater than other to axis of length **a**, the shape anisotropy constant is:

$$\boxed{K_S = \frac{(N_a - N_c)M^2}{2}}$$

N_a and N_c are demagnetizing factors.



Magnetization Produces Apparent Suface Pole Distribution



Demagnetizing Field Due to Apparent Surface Pole Distribution

• Shape anisotropy is significantly greater than the crystal anisotropy. For example, iron has $K = 4.8\times10^5$ erg cm^{-3} whereas $K_s = 1.85\times10^7$ erg cm^{-3}.
• As physical dimensions are decreasing, we produce magnetic materials with one or more dimensions on nm scale, the possibility of anisotropy due to shape increases.

Ferromagnetic exchange interaction

In a magnetized iron crystal, all the atomic magnetic moments are aligned in the same direction. The reason for the alignment of the moments is not the magnetic forces between the moments as the magnetic potential energy of interaction is small indeed smaller than the thermal energy.

The iron atom has the electron structure [Ar]$3d^6 4s^2$. An isolated iron atom has only the 3d subshell with four of the five orbitals unfilled. Hund's rule says that the electrons try to align their spins so that the five 3d orbitals contain two paired electrons.

When the spins are parallel as per Pauli exclusion principle, the electrons must occupy orbitals and hence possess different spatial distributions. This results in a smaller Coulombic repulsion energy between the electrons compared with the case where the electrons have opposite spins and are in the same orbital. Two electrons parallel their spins not because of the direct magnetic interaction between the spin magnetic moments but because of the Pauli exclusion principle and the electrostatic interaction energy. Together they constitute an exchange interaction, which forces two electrons to take m_s and m_l values that result in the minimum of electrostatic energy.

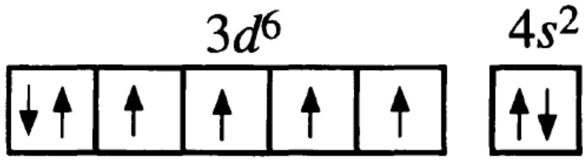


Figure 8.18 The isolated Fe atom has four unpaired spins and a spin magnetic moment of 4β.

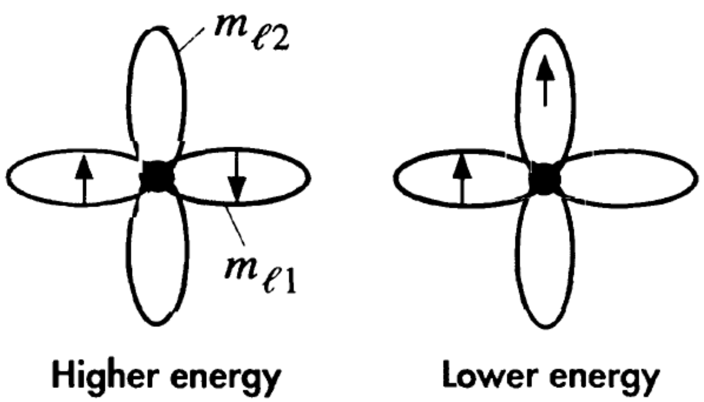
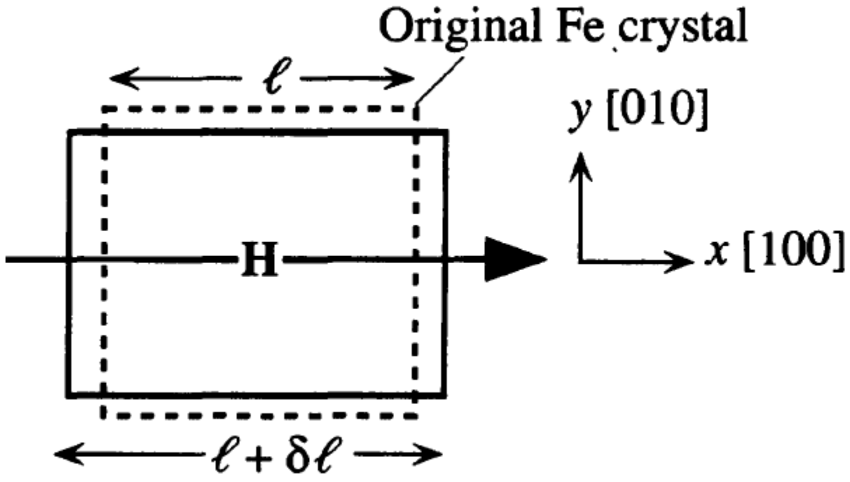


Figure 8.19 Hund's rule for an atom with many electrons is based on the exchange interaction.

Thus, the majority of 3d electrons spontaneously parallel their spins without the need for the application of an external magnetic field. The number of electrons that actually parallel their spins depends on the strength of the exchange interaction, and for the iron crystal this turns out to be about 2.2 electrons per atom.

Magnetostriction

By applying stress to a ferromagnetic crystal along a certain direction, the interatomic spacing changes not only along this direction but also in other directions and hence changes the exchange interactions between the atomic spins. This would lead to a change in the magnetization properties of the crystal. In the converse effect, the magnetization of the crystal generates strains. For example, when an iron crystal is magnetized along the [111] direction by a strong field, the atomic spins within domains are rotated from their easy directions toward the hard [111] direction. These electron spin rotations involve changes in the electron charge distributions around the atoms and therefore affect the the interatomic spacing. When an iron crystal is placed in a magnetic field along an easy direction [100], it gets longer along this direction but contracts in the transverse directions [010] and [001]. The reverse is true for nickel. The longitudinal strain along the direction of magnetization is called the magnetostrictive constant. The magnetostrictive constant X depends on the crystal direction and may be positive (extension) or negative (contraction). Further, X depends on the applied field and can even change sign as the field is increased; for example, X for iron along the [110] direction is initially positive and then, at higher fields, becomes negative.



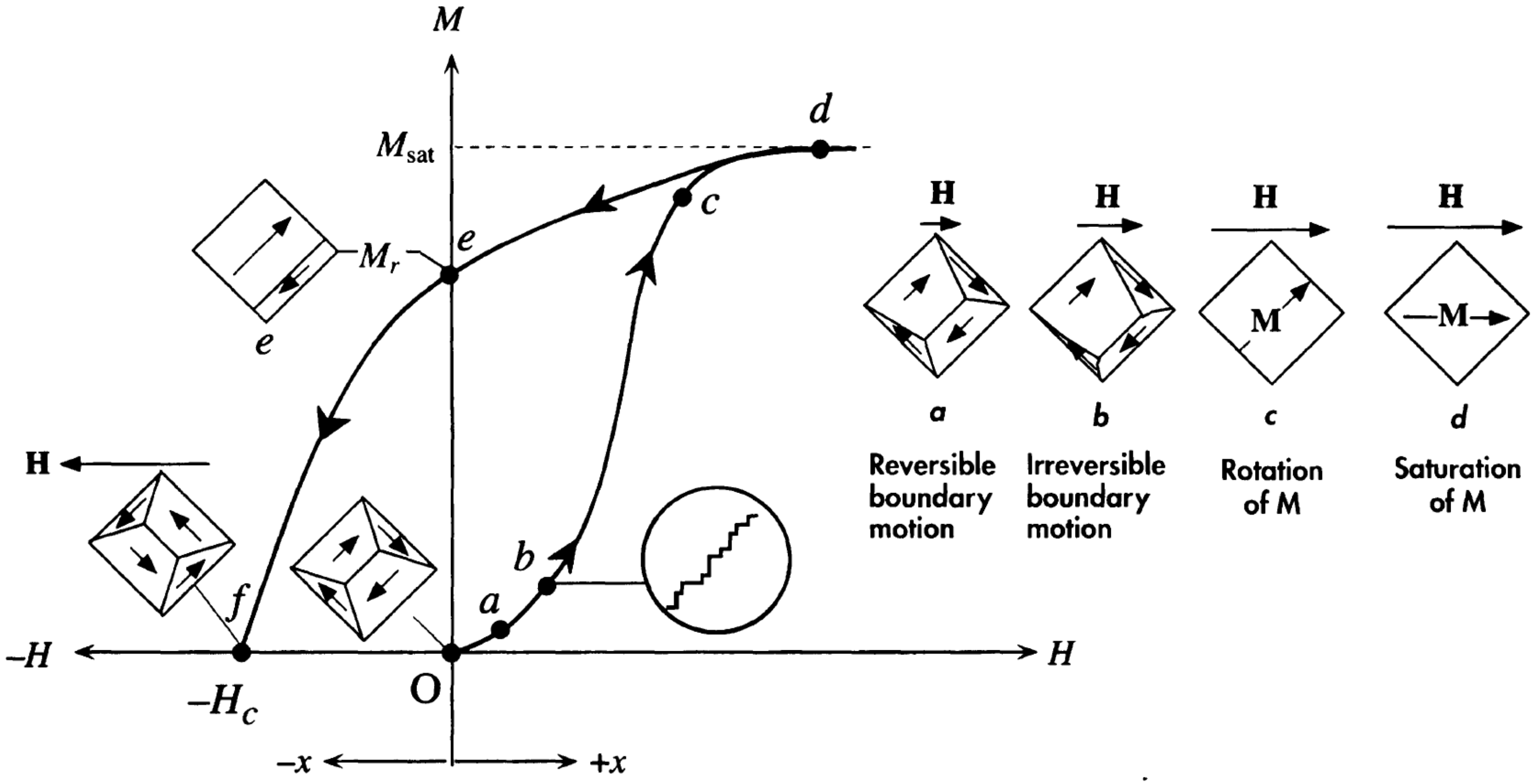
The magnetostrictive constant X can be controlled by alloying metals. For example, X along the easy direction for nickel is negative and for iron it is positive, but for the alloy 85% Ni-15% Fe, it is zero. In certain magnetic materials, X can be large ($>10^{-4}$) which has opened up new areas of sensor applications based on the magnetostriction effect. For example, it may be possible to develop torque sensors for automotive steering applications by using Co-ferrite type magnetic materials.

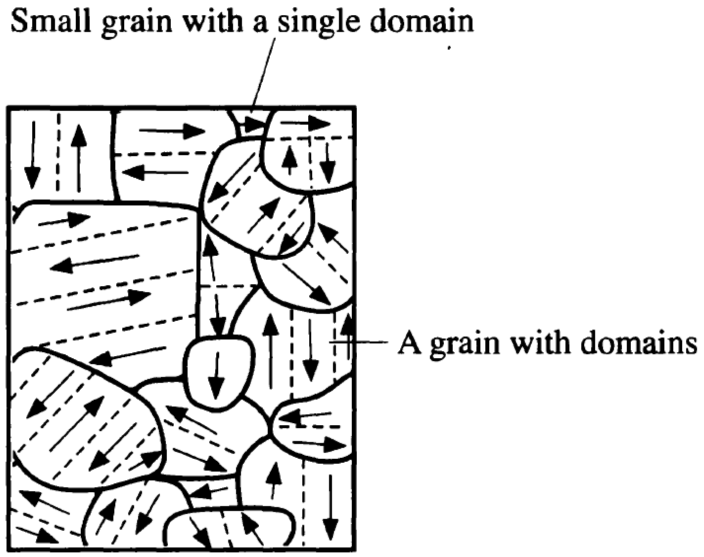
Domain Wall Motion

The magnetization of a single ferromagnetic crystal involves the motions of domain boundaries to allow the favorably oriented domains to grow at the expense of domains with magnetizations directed away from the field. The motion of a domain wall in a crystal is affected by crystal imperfections and impurities and is not smooth. Due to magnetostriction, there is a change in the distortion of the lattice across the boundary. We also know that crystal imperfections such as dislocations and point defects also have strain and stress distributions around them. Domain walls and crystal imperfections therefore interact with each other. The motion of a domain wall in a crystal is therefore not smooth but rather jerky. The wall becomes pinned somewhere by a defect or an impurity and then needs a greater applied field to break free. Once it snaps off, the domain wall is moved until it is attracted by another type of imperfection. Each time the domain wall is snapped loose, lattice vibrations are generated, which means loss of energy as heat. The whole domain wall motion is nonreversible and involves energy losses as heat to the crystal.

Sudden changes in the magnetization induce eddy currents that dissipate energy via Joule heating (domains have a finite electrical resistance). These processes involve energy conversion to heat and are irreversible. Sudden jerks in the wall motions lead to small jumps in the magnetization of the specimen as the magnetizing field is increased; the phenomenon is known as the Barkhausen effect.

M versus H behavior of a previously unmagnetized polycrystalline iron sample





(a) Under very small fields, the domain boundary motion is reversible.
(b) The boundary motions are irreversible and occur in sudden jerks.
(c) Nearly all the grains are single domains with saturation magnetizations in the easy directions.
(d) Magnetizations in individual grains have to be rotated to align with the field H.
(e) When the field is removed, the specimen returns along cf to e.
(f) To demagnetize the specimen, we have to apply a magnetizing field of Hc in the reverse direction.