PHY331
Magnetism

Lecture 7

Last week…

- We derived a quantum theory of Paramagnetism.

$$\chi = \frac{\mu_0 N g^2 J(J+1)\mu_B^2}{3kT} = \frac{constant}{T}$$

- Showed that this also confirmed Curie's Law.
- Looked briefly at Ferromagentism. Studied hystersis curves of magnetisation versus magnetic field.

This week…

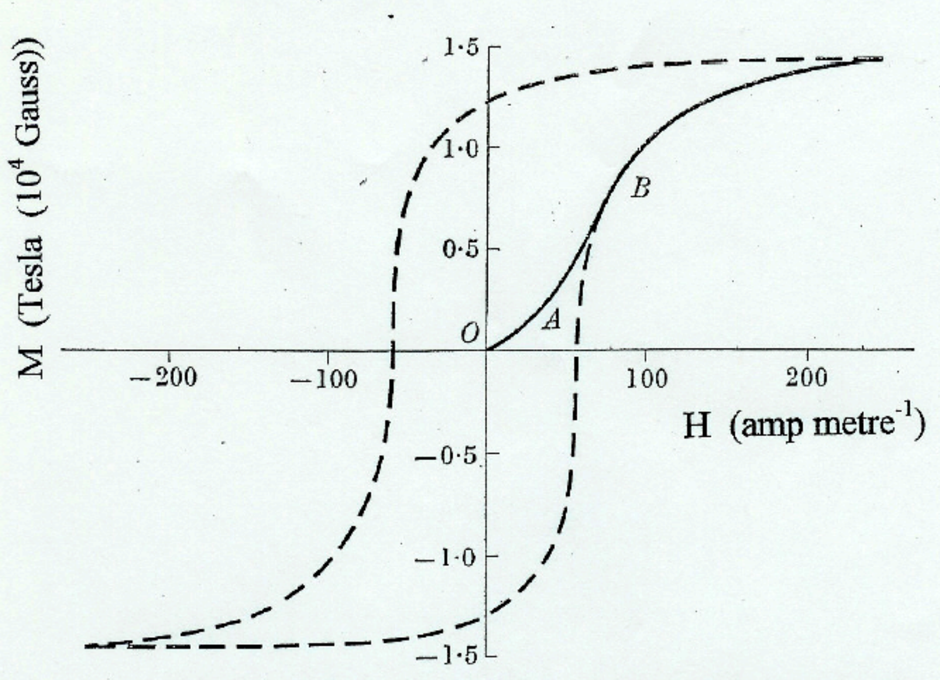
- Hysteresis curves
- The domain theory of Ferromagnetism.
- Motion of domain walls.
- Stabilization of domain walls and domain wall thickness.
- Paramagnets vs ferromagnets.

Hysteresis curve for a ferromagnet

A **wide loop** is good for **permanent magnets,** since it is hard to demagnetise them.

A **narrow loop** is good for **transformer cores,** H_C is small as the area inside the loop is equal to the energy lost in going round a cycle,

so they are easy to demagnetise each (50 Hz) cycle



Magnetization curve (full line *OABS*) and hysteresis loop (broken line) for iron.

The domain theory of ferromagnetism

- In a ***paramagnet***, the increasing magnetisation *M* is due to the ***increasing alignment of the magnetic dipoles*** (in the $-\mu.B \approx kT$ magnetic *versus* thermal "competition")

- For a ***ferromagnet***, ***extremely large values of*** *M* can be created by the application of ***very small applied fields*** *H*

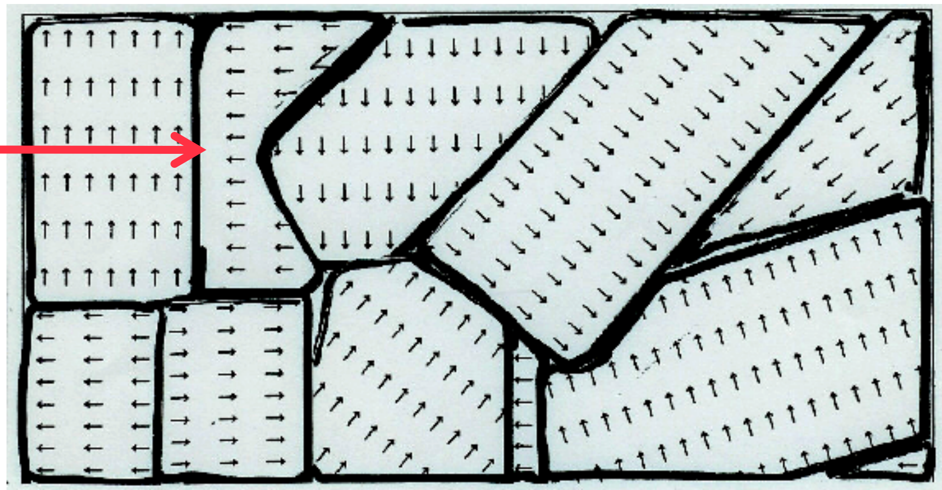
- To produce ***such large*** *M* values by ***direct alignment of the magnetic moments*** would require ***applied fields*** about 1000 times greater

Does this mean the magnetic moments are ***already aligned?*** Yes, we have ***"spontaneous magnetisation"***

The applied field H is ***not creating the magnetisation***, it is ***rearranging the spontaneous magnetisation*** which is already in the sample.

Pierre Weiss (1907) suggested that, a ferromagnetic material consists of ***small macroscopic regions*** (called ***domains***), which are already spontaneously magnetised.

Edges of domains are Called domain 'walls'. Width of wall can be a few 100 atoms wide.



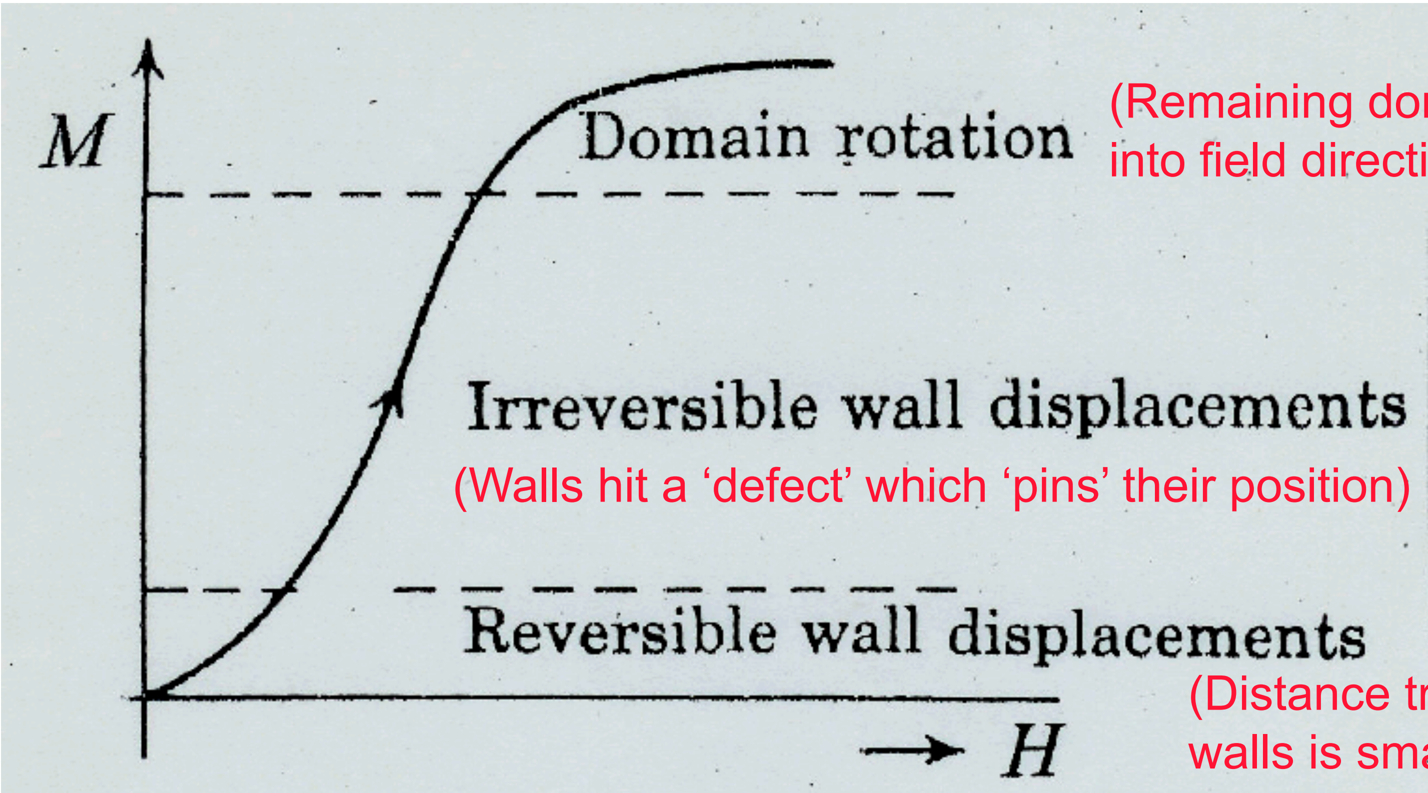
The magnitude of the ***magnetism*** M ***of a sample***, is equal to the vector sum of the ***magnetisation of the domains***

The regions of spontaneous magnetisation obviously ***already exist*** and the external field H produces an overall magnetisation M by ***altering their distribution*** (size and distribution).

This model gives a qualitative description of the ***characteristic shape*** of the M v. H ***magnetisation curve***

Domain model for the magnetisation of a ferromagnet

Displacement of domain walls ‘eat’ away the unfavourable domains whose direction is not aligned with the applied magnetic field.

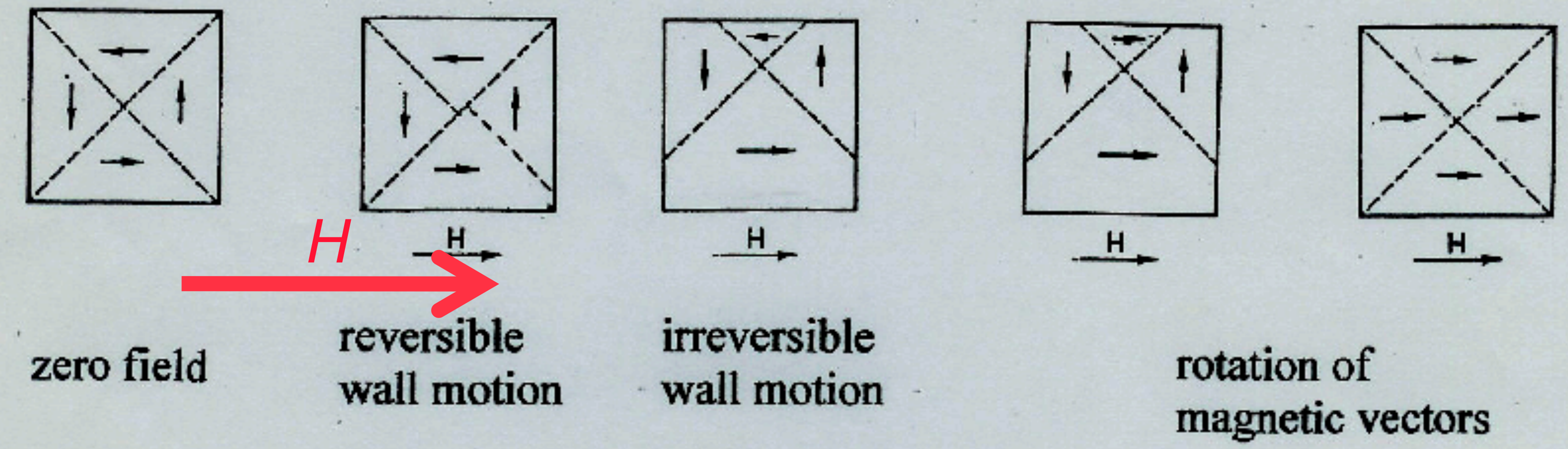


There are ***two main mechanisms*** by which a ***ferromagnet is magnetised*:**

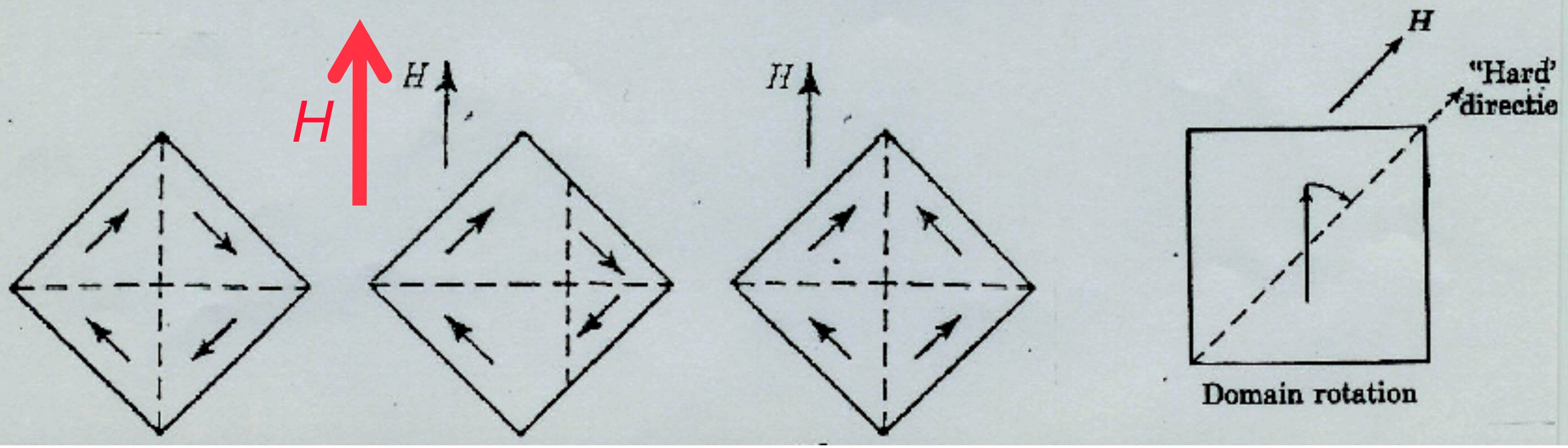
1. ***Growth of domains*** with ***favourably orientated magnetisation vectors*** (this proceeds by both reversible and irreversible domain wall motions).

2. ***Rotation of the magnetisation vectors*** "into the field direction"

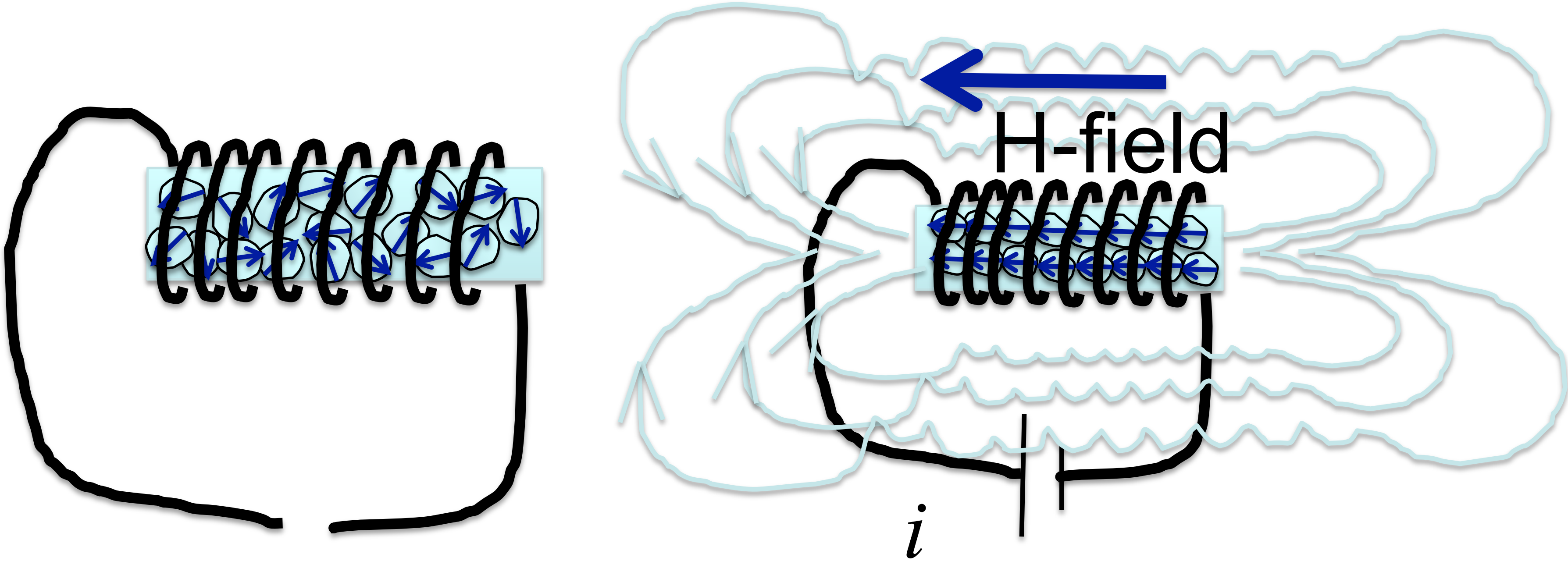
Note that the ***irreversible domain wall motions*** give rise to the observed ***hysteresis effects***



there are several (equivalent) illustration of this behaviour



Magnetisation



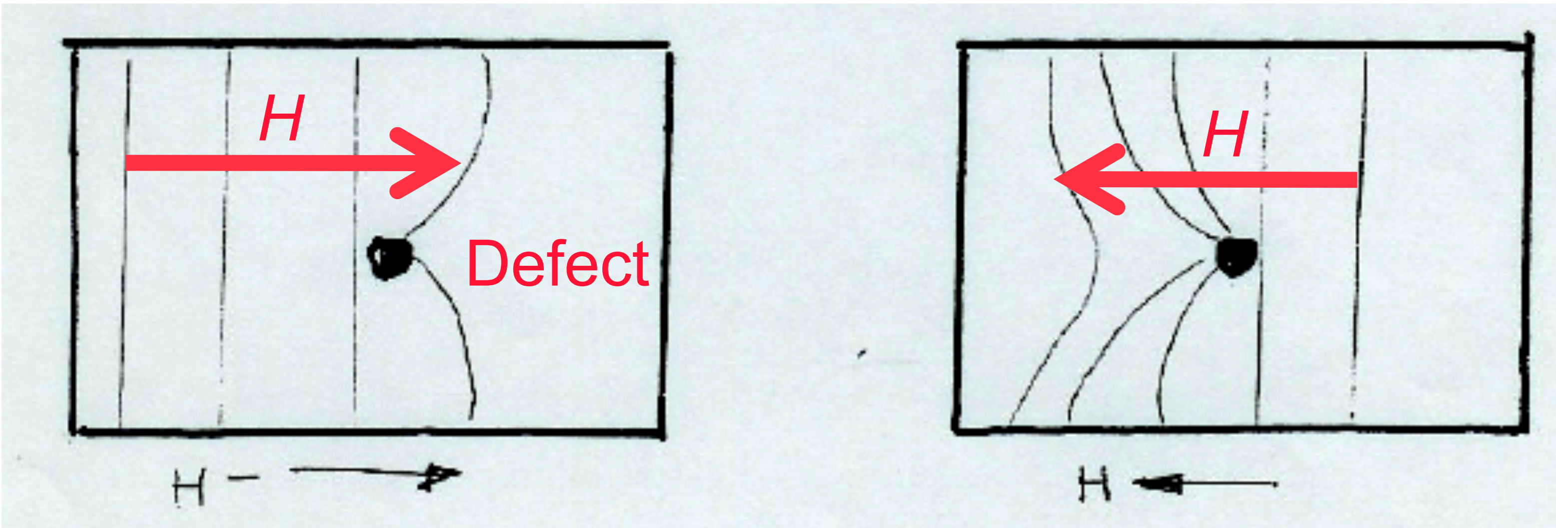
No current flows, no magnetising H-field. Magnetic domains in metal have different orientation – no strong external B-field.

When current flows, magnetising H-field in the metal. Magnetic domains in metal align with field - strong external B-field.

What makes a domain wall motion irreversible?

The motion of the walls (or boundaries) is strongly influenced by ***defects or impurities*** in the sample.

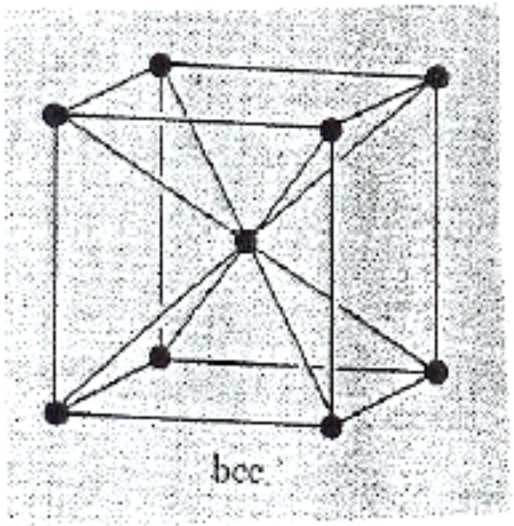
The motion of domains away from a defect is not reversible when an applied H-field is reversed.

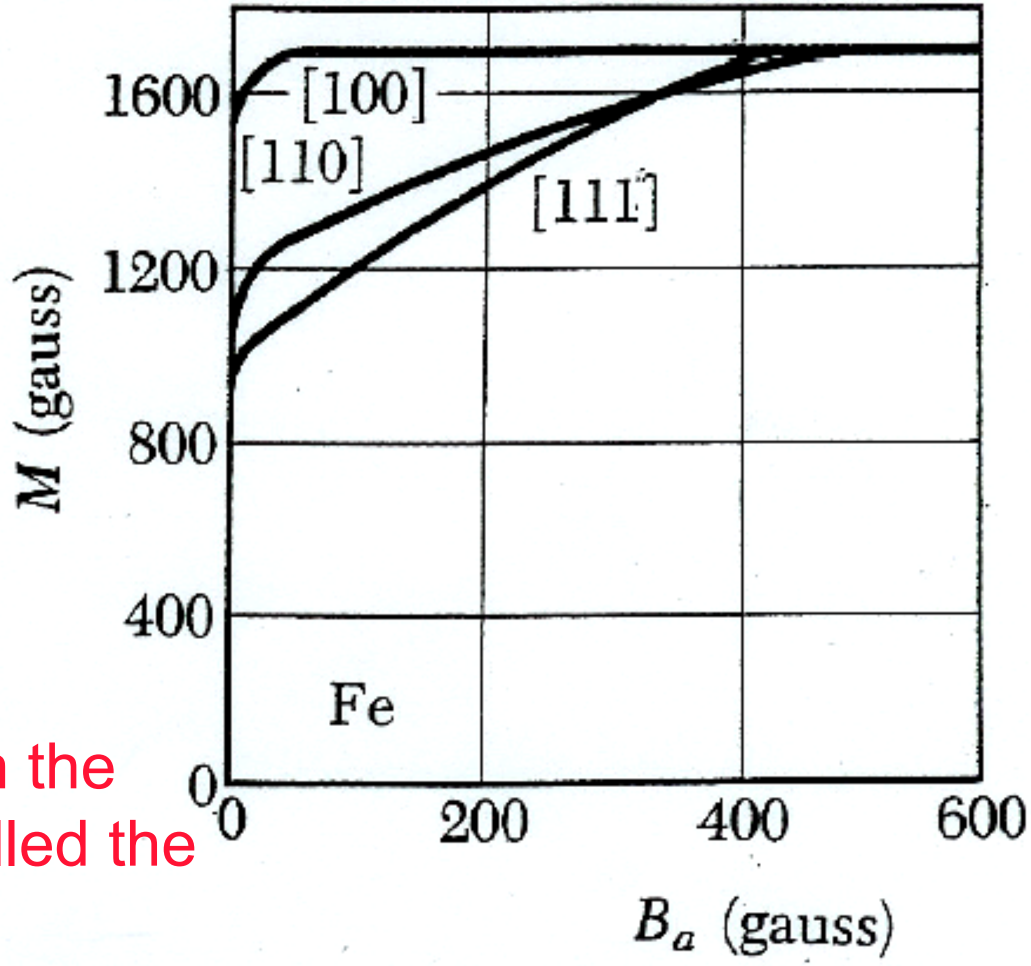


Prepare single crystals of ferromagnetic materials.

Measure magnetization as a function of field direction. Find an anisotropy. Define an 'easy direction'.

Iron crystal





Easier to magnetize Fe in the [100] direction. This is called the 'easy' direction.

Development of a stable domain configuration

(what determines the equilibrium structure of the domains?)

The total energy of a ferromagnetic crystal has contributions from 3 mechanisms:

(1) The ***magnetostatic energy*** (the intrinsic energy stored in a magnetic field $B^2/2\mu_0$ per unit volume).

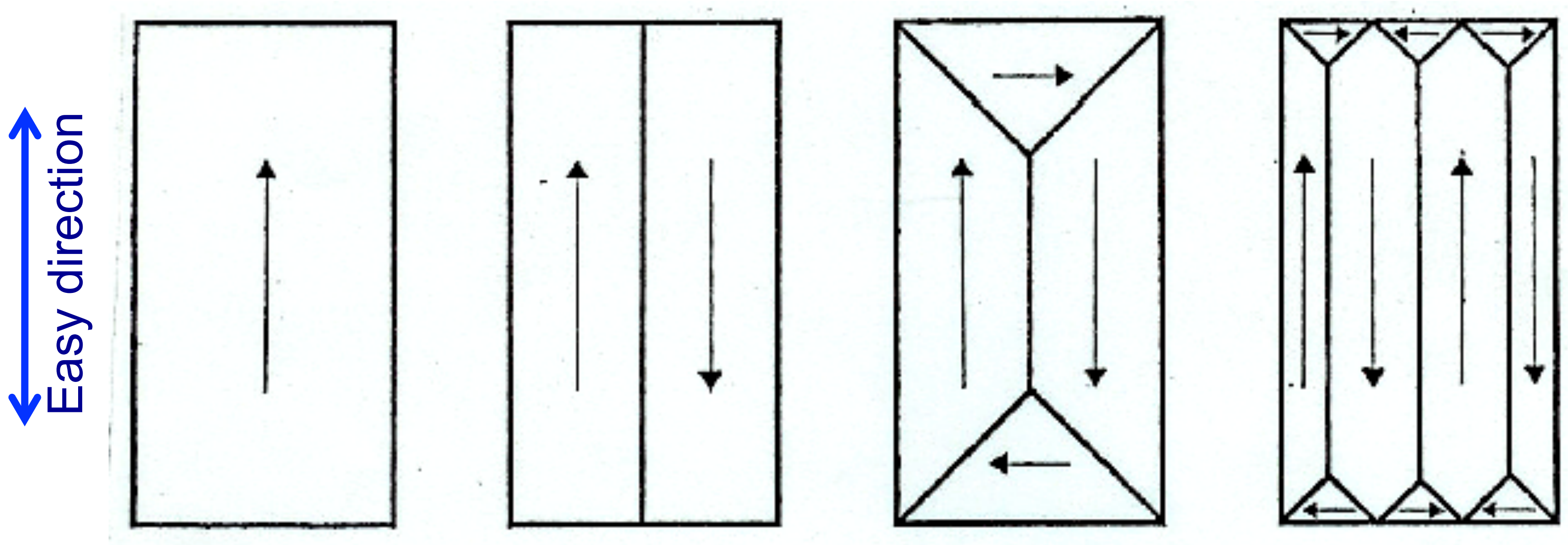
(2) The ***anisotropy energy*** (which measures the energy penalty of materials magnetised in unfavourable directions – i.e. energy penalty paid when a domain is magnetised away from the easy direction).

(3) The ***exchange energy*** (which concerns the mechanisms by which neighbouring magnetic dipoles are aligned).

Obviously the ***sum*** of (a), (b) and (c) must be ***minimised***

See discussion in Hook and Hall.

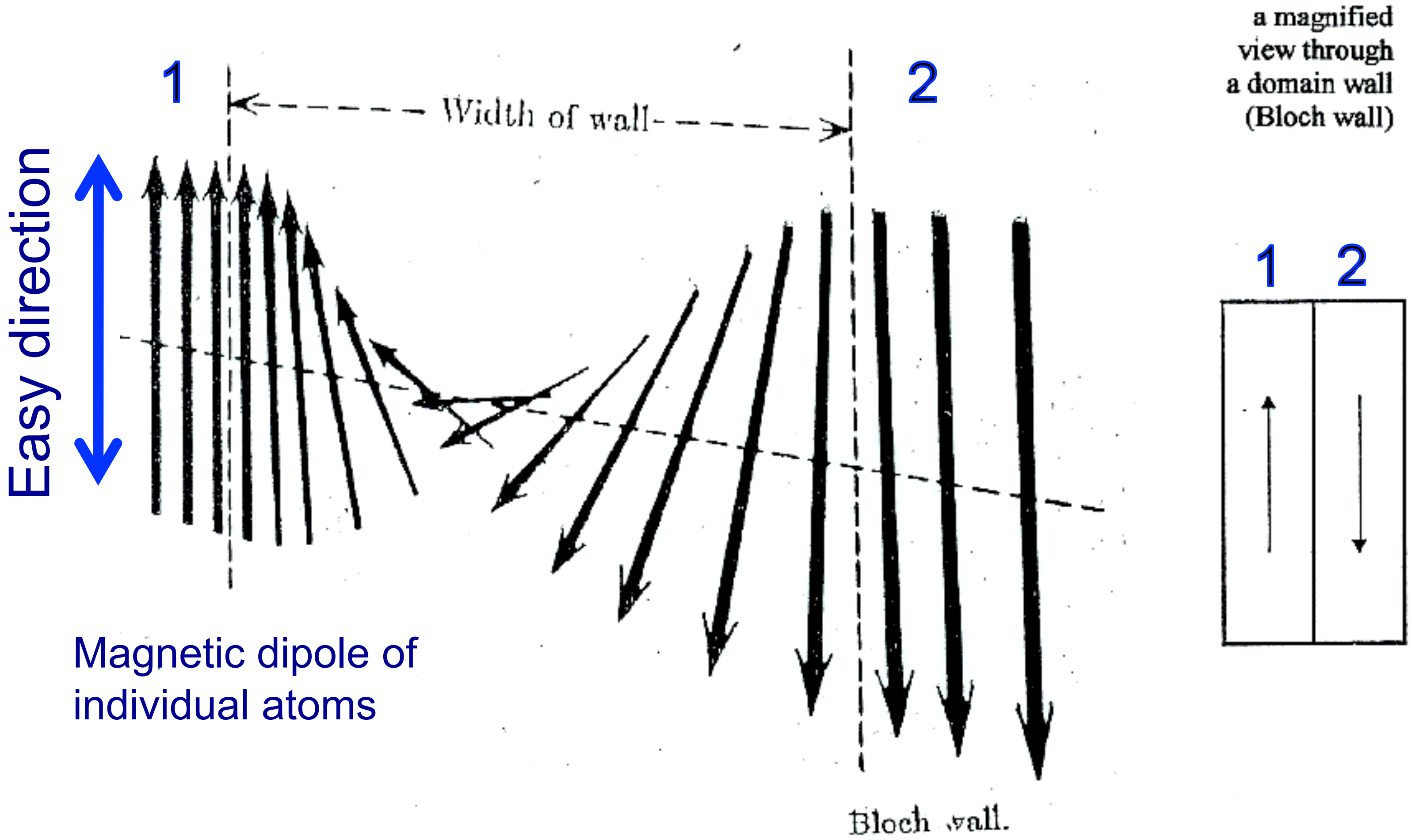
1. Magnetostatic energy



Division into smaller domains reduces the total volume of the external field and therefore reduces the magnetostatic energy. N.B. in this figure there is no applied *H*-Field

- Why does the process of ***subdivision of domains not continue indefinitely***? What is the ***competing***/controlling ***mechanism***?

A magnified view through a domain wall (Bloch wall)



Bloch-wall can extend over 100s of atoms – slow rotation of magnetic dipole moment between neighbouring atoms

‘Slow’ rotation of magnetic dipole across the wall occurs as large energy cost in having neighbouring atoms with different dipole orientation (**exchange energy**).

Within the domain wall, the majority of the magnetic dipole moments may be pointing out of the easy direction. This will then contribute to the **anisotropy energy**.

As domains get smaller, **magnetostatic energy reduces**, however have more atoms found in the domain walls, and so the **anisotropy energy** grows.

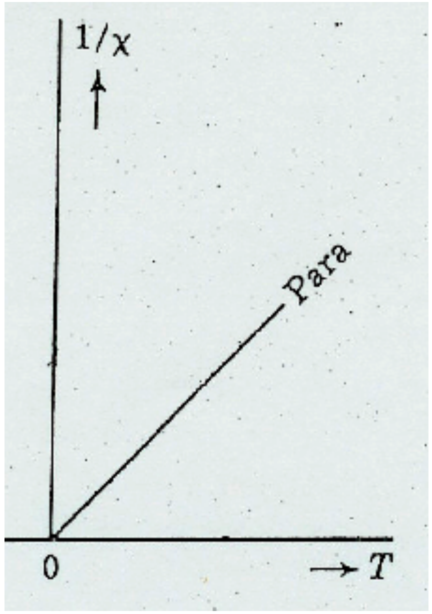
Resulting balance between **anisotropy**, **exchange** and **magnetostaic** energies determine overall structure of domains and leads to establishment of an equilibrium structure.

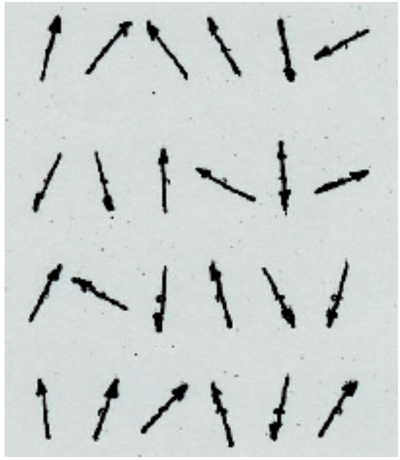
What causes the alignment between neighbouring Magnetic dipole moments?

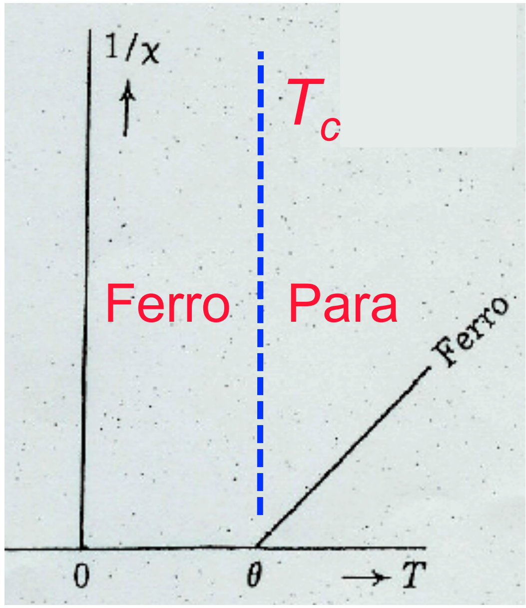
Several mechanisms have been proposed, including a ***quantum mechanical one*** based on the ***exchange of electrons*** between neighbouring atoms.

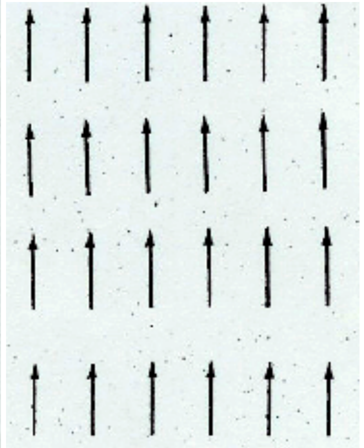
This is why the ***third contribution*** to the magnetic energy. It has the generic name of ***"exchange energy"*.**

Spontaneous magnetisation









1) The paramagnet

\# a ***permanent magnetic moment*** on each magnetic atom, leads to a ***random, dynamic, configuration*** of the magnetic moments ("magnetic *versus* thermal competition")

$$\chi = \frac{C}{T}$$

2) The ferromagnet

A *paramagnetic state above* the ***Curie temperature*** T_C ***Curie-Weiss Law*** is in the paramagnetic regime

$$\chi = \frac{C}{T - \theta}$$

Since M exists for $H = 0$

$$\chi = M/H$$

there is a ***spontaneous magnetisation*** in each domain for, $T < T_C$

Heating past T_c

- If heat permanent magnet past T_c and then cool – ‘destroy’ domain structure. On cooling, have a random equilibrium structure of domains with no net magnetization.
- Therefore heating a permanent magnet above T_c turns it back to a regular ferromagnetic solid.

Summary

- Discussed domain theory of Ferromagnetism.
- Saw there is a motion of domain walls with applied magnetic field.
- Stabilization of domain walls due to competition between magnetostatic energy, anisptropy energy and exchange energy (see next week).
- Forms domains having finite wall thickness.