

## 5. NANOMAGNETISM

As in every chapter that we have seen in this course, it is a question of understanding what happens to a magnetic system when its size is decreased down to the nanoscale.

### 5.1. FERROMAGNETISM

At the single-electron level, a magnetic moment (known as spin) arises due to the "orbital motion". This magnetic moment is quantized in units of the Bohr magneton

$$\mu_B = \frac{qh}{4\pi m_e} = 9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2$$

This magnetic moment can interact with an external magnetic field, as an electrical current does.

In most materials (non-magnetic) there is an equal number of electrons with up and down spins, and therefore the net magnetization of the material is zero.

For example, transition metals have unbalanced electronic spins and display magnetic characteristics.

Ferromagnetic materials are those for which different electron spins couple by exchange interaction and order in the same direction.

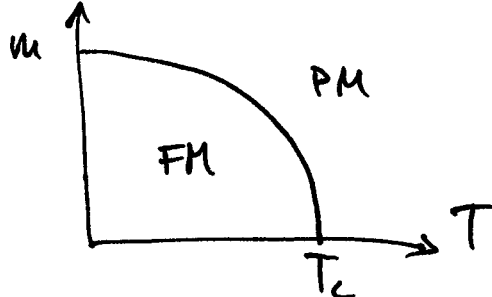
## Exchange Interaction: slide 1

As a result of the overlapping of the electronic orbitals of neighboring atoms, some materials will display a ferro-magnetic ordering arising from the orientation of atomic spins in space

- Ferromagnetic ordering:  $\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow \quad \vec{m} > 0$
- Antiferromagnetic ordering:  $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow \quad \vec{m} = 0$
- ~~ferro~~ ferrimagnetic ordering:  $\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow \quad \vec{m} > 0$

\* Exchange coupling energy:  $E_{ex} = J \vec{S}_i \cdot \vec{S}_j$

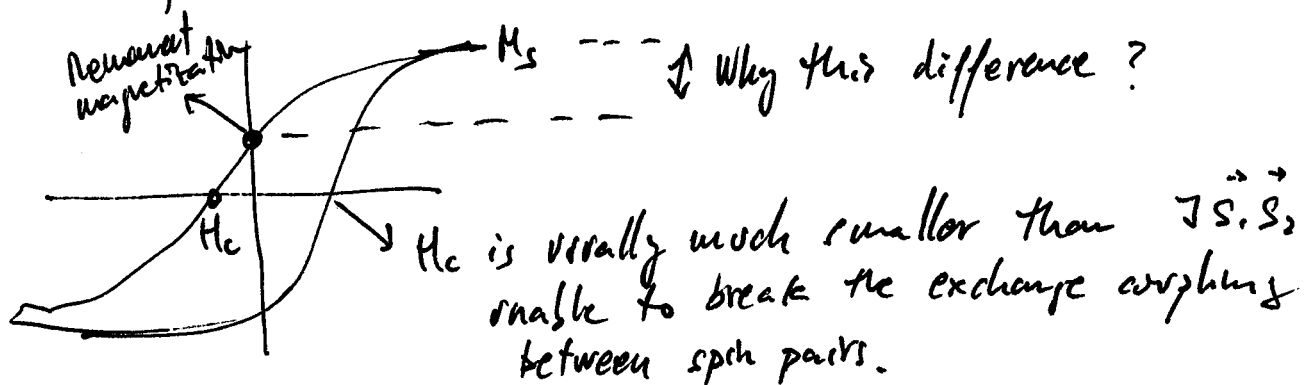
\* Curie Temperature:  $T_c$



if  $k_B T > E_{ex} \Rightarrow \text{no FM}$

## Magnetic hysteresis:

Magnetic materials usually display magnetic hysteresis as a response to an externally applied field.

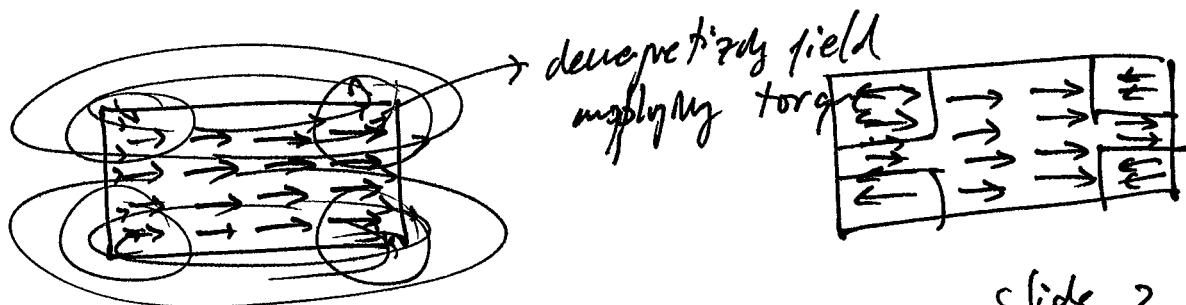


## Magnetic Domains: ~~slide~~

Most magnetic materials which present ferromagnetic coupling at temperatures below the Curie temperature ~~do~~ not behave as permanent magnets. In other words, they don't display any signs of magnetization. Why?

## Demagnetizing fields:

After magnetizing a ferromagnetic material with a magnetic field, demagnetizing fields tend to decrease the total magnetic moment of the material, and eventually eliminate it completely.



slide 2

In the process, magnetic domains form.

Different materials present different demagnetizing relaxation times.

→ Best permanent magnets

- \* High saturation magnetization ( $M_s$ )
- \* High remanent magnetization ( $M_r$ )
- \* High coercivity ( $H_c$ )
- \* Long relaxation times ( $T_m$ )

↳ depends on temperature

## 5.2. NANOMAGNETISM - SINGLE DOMAIN SYSTEMS

It is easy to understand <sup>how</sup> ~~when~~ things will change when considering magnetic materials and size:

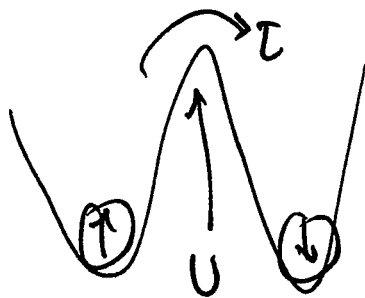
System dimensions  $<$  single-domain size ( $\sim 100 \text{ nm}$ )

- When a magnetic system is smaller than  $\sim 100 \text{ nm}$  (single domain size), its behavior will be (in general) different than the same system at the macroscale slide 3
- In addition, for smaller sizes, quantum mechanical effects will take place and change the behavior even more drastically

### Magnetic anisotropy:

Shape or magnetocrystalline interactions may generate a preferred direction for the magnetisation to lie along. As a result, an anisotropy barrier develops separating opposite orientations of the magnetic moment of the nanostructure

slide 4



Arrhenius law:

$$\tau = \tau_0 \exp\left(\frac{U}{k_B T}\right)$$

$$T_B = \frac{U}{k_B \ln(\tau/\tau_0)}$$

## Magnetic Quantum Tunneling slide 5

At sufficient low temperatures,  $T$  would ~~increase~~ increase and the relaxation time decrease down to zero. However, for small-enough magnetic nanostructures, the magnetic moment can still flip quantum-mechanically.

This effect is more pronounced the smaller the system is. Particularly important in molecular magnets or individual "solid-state" spins (see below).

## Applications of single-domain nanostructures:

- Bio-medical applications to be seen in next chapters
- Memory storage (Hard drives) slides 6 and 7

## 5.3. SINGLE MOLECULE MAGNETS AND SINGLE SPINS

For low enough sizes, quantum mechanics governs the magnetic nature of systems. For low spin systems, such as a single-molecule magnet (SMM) or a single-spin embedded in a solid state matrix, the energy of the different spin projections in space is quantized.

→ see presentation slides to explain this slides 8-12

## S.4. QUANTUM COMPUTING AND INFORMATION

In classical computers, we encode information with bits, which present two well-defined states 0 and 1

Coding of numbers (binary)

$$0 \rightarrow 0000$$

$$1 \rightarrow 0001$$

$$2 \rightarrow 0010$$

$$3 \rightarrow 0011$$

$$4 \rightarrow 0100$$

$$5 \rightarrow 0101$$

⋮

A quantum computer relies on quantum bits, which can be found in any arbitrary superposition of two states

$$|\psi\rangle = a|0\rangle + b|1\rangle$$

Therefore, one can code all possible numbers with a single sequence of qubits. For example,

$$010|\psi\rangle \rightarrow 4 \text{ if } |\psi\rangle = 0 \\ \rightarrow 5 \text{ if } |\psi\rangle = 1$$

slide 13

Quantum computing algorithms would take advantage of the quantum parallelism to compute some problems much faster than classical computers.

slide 14

Problems that:

- based on guessing answers to find a solution
- # answers to check  $\propto$  # inputs
- all answers take the same amount of time to check
- No info on what kind of answer is better. Random checking is as efficient as ordered checking.

Existing algorithms:

- Shor factorization
- Grover search

A quantum computer would solve such problems in a potential amount of time (potential with the amount of inputs), which for a classical computer would be exponential.

Other applications: A quantum computer would be a perfect simulator of quantum systems. It would allow studies not possible with current experimental facilities.

Desired list for quantum computing: slide 15

- scalable physically to increase the number of qubits
- ✓ → Initialization of qubits to a desired value
- ✓ → Quantum gates operating faster than decoherence
- ✓ → Universal set of gates (single-qubit and CNOT)
- ✓ → Ease in reading the qubits' state

slides 16 and 17 (Morello)

Optional to talk about spintronics / thin films