MAGNETISM AND MAGNETISATION PROCESSES IN NANOSTRUCTURED SYSTEMS

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Magnetisation processes define the applicative properties of materials, of which the magnetisation is used as a source of a magnetic field or of a magnetic flux. All these materials are Fe, Co or Ni based. They differ by the strength of their coercivity, i.e. their ability to resist an applied magnetic field, $\mu_0 H_{app}$, which tends to change the orientation of the magnetisation. From extremely soft to extremely hard materials, the coercive field, $\mu_0 H_c$, at which the magnetisation finally follows the applied field, increases by more than 6 orders of magnitude. Soft materials are used in magnetic circuits, transformers or sensors; hard materials are used to make motors, actuators or generators; materials with medium coercivity are used as storage media.

The recent discovery of behaviours which are specific to nanomaterials, has open a new period in the search for magnetic materials. The usual concepts used to describe magnetisation processes at the macroscopic scale do not apply. Properties often superior to those obtained at the macroscopic scale may emerge.

In the first part of this lecture, we will review the specific intrinsic magnetic properties of aggregates, and in the second part, we will describe magnetisation processes in nanoparticles. The third part will concentrate on the description of various specific processes characterising systems formed of exchange-coupled magnetic nanoparticles.

1- MAGNETISM IN AGGREGATES

1-1 Magnetic moment

Moment value remains the same as in the bulk in systems where magnetic electrons are strictly localized (insulating systems, rare-earth magnetism). In itinerant electron systems : enhancement of the 3d moment due to electron localisation for surface atoms (seen in particular in Fe, through enhancement of the hyperfine field, derived from Mössbauer spectroscopy at low T).

Specific enhancement of the orbital moment seen by XMCD. Due to the low symmetry of the environment at surfaces.

Onset of magnetism in normally non-magnetic systems (i. e. Rh). Another illustration of the increased electron localisation.

1-2 Magnetic order in aggregates

Type or order : not significantly affected in 3d ferromagnetic systems (inherently associated to the itinerant nature of the magnetic electrons).

Local super-exchange interactions affected in insulating systems (change in coordinence for surface atoms, atom displacements in the bulk) . Non-collinear magnetic arrangements and spin-glass like structures.

Reduction in ordering temperature T_c, associated to reduction in coordinence.

Modification of the temperature dependence of the magnetisation, correlated to the modification of the spectrum of magnetic excitations (quantification of the energy spectrum).

1-3 Magnetic anisotropy in aggregates

Large anisotropy associated to symmetry breaking for surface atoms (same effect as for surface atoms in films); also linked to increased orbital moment.

Due to averaged spherical symmetry, the bulk anisotropy should be small, but (i) statistical deviations due to small sizes and (ii) local deformations must be considered.

2 – MAGNETISATION PROCESSES AT THE NANOSCALE

2-1 Coherent rotation versus nucleation/propagation

Energy barrier for reversal. Possible processes to overcome the barrier. Comparison of energy terms involved in nucleation/propagation and in coherent rotation. Critical dimension below which coherent rotation dominates. How defects manifest themselves at small sizes.

2-2 Thermal activation – Macroscopic tunnelling

Field dependence of the energy barrier characterising coercivity. Thermal activation over the barrier. Arrhenius law. Possibility of tunnelling. Different behaviours observed in metals and insulators. Coupling to the environment.

2-3 Single-domain particles

Competition between domain wall energy and demagnetising field energy. Single domain state favoured at small sizes. Evaluation of critical radius below which single domain state is stable.

2-4 Superparamagnetism

Thermal activation in very small particles. Characteristic time required to overcome the energy barrier. Can the anisotropy be deduced from the time required to overcome the barrier ?

3 MAGNETISATION PROCESSES IN COUPLED NANOSYSTEMS

3-1 Anisotropy and characteristic correlation length in exchange-coupled nanocrystals

Assembly of randomly oriented exchange-coupled nanoparticles. Assuming collinearity of all moments, anisotropy is a bulk term whereas exchange is a surface term. At small sizes, exchange dominates, at large sizes, anisotropy dominates: Evidence for the existence of a characteristic correlation length, ξ. Evaluation of ξ and evaluation of anisotropy over ξ.

3-2 Ultra-soft magnetic properties and remanence enhancement

Depending on the value of the local anisotropy, macroscopic correlation length with extremely small anisotropy or grain-size correlation with large anisotropy may exist. Leads to ultra-soft magnetic properties in the former case, leads to remanence enhancement effects,in the latter case.

3-3 Coercivity in Nanocomposites

Due to exchange coupling between soft and hard grains, reversal of the soft grains is frozen. Finite nucleation field required to reverse the magnetisation in the soft grains. Propagation of magnetisation reversal from the soft to the hard grains. Which prospect for magnetic nanocomposites ?

3-4 Exchange bias

Exchange-bias : a phenomenon characterising interface coupling between a ferromagnet and an antiferromagnet. Leads to ferromagnet shifted hysteresis loop. Possible coupling schemes. Evaluation of the bias-field. Discrepancy between models and experiments.

Large exchange-bias for ferromagnetic nanoparticles within an antiferromagnetic matrix. Enhancement of the blocking temperature, at which superparamagnetism appears. Why is the bias-field much larger than in coupled layers ?

3-5 Giant-magnetostriction in multilayers

Large magnetostriction together with large magnetic susceptibility : two contradictory requirements. Magnetostriction and magnetic susceptibility in soft/magnetostrictive multilayers: a new type of magnetic nanocomposites.

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