MAGNETISM AND MAGNETISATION PROCESSES IN NANOSTRUCTURED SYSTEMS

D. Givord
Laboratoire Louis Néel, CNRS, 25 avenue des Martyrs, B.P. 166, 38042 – Grenoble – cedex 9

Contents

1 – MAGNETISM IN AGGREGATES
1-1 Magnetic moment in aggregates
1-2 Magnetic order in aggregates
1-3 Magnetic anisotropy

2 – MAGNETISATION PROCESSES AT THE NANOSCALE
2-1 Coherent rotation versus nucleation-propagation
2-2 Thermal activation
2-3 Single domain particles
2-4 Superparamagnetism

3 – MAGNETISATION PROCESSES IN COUPLED NANOSYSTEMS
3-1 Anisotropy and characteristic correlation length in exchange-coupled nanocrystals
3-2 Ultra-soft magnetic properties and remanence enhancement
3-3 Coercivity in Nanocomposites
3-4 Exchange-bias
3-5 Giant-magnetostriction in multilayers

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, \( \mu_0H_{app} \), which tends to change the orientation of the magnetisation. From extremely soft to extremely hard materials, the coercive field, \( \mu_0H_c \), 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 opened 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 coordination 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 coordination.
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, $\xi$. Evaluation of $\xi$ and evaluation of anisotropy over $\xi$.

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.
BIBLIOGRAPHY

Finite-size effects in fine particles: magnetic and transport properties
X. Batlle and A. Labarta

Classical and quantum magnetization reversal studied in nanometer-sized particles and clusters
W. Wernsdorfer

Nanoscale materials development for future magnetic applications
M.E. McHenry and D.D. Laughlin, Acta; Mater. 48 (2000) 223

The exchange-spring magnet: a new material principle for permanent magnets
E. Kneller and R. Hawig
IEEE Trans Mag. 27 (1991) 3588

Giant energy product in nanostructured two-phase magnets
R. Skomski and J.M.D. Coey

Exchange bias
J. Nogués and Ivan K. Schuller

Exchange anisotropy—a review
A E Berkowitz and K Takano

Mechanisms for exchange bias
R.L. Stamps