Open questions in Magnetism

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For scientists working in a given field, it is common to think that all basic phenomena in the concerned field have already been discovered and this field will develop in the future under the conditions that applications emerge, exploiting the results of fundamental research.

Many recent development in magnetic material research emerged from application-oriented activities. It remains however that a series of original results were recently discovered which were essentially unexpected and contradict the above argument so magnetic ordering in this type of systems.

In this lecture, I will briefly describe the general magnetic properties of matter and will try to identify the properties which are well understood from those which are not. I will not speak of the new experimental tools were developed in the early 90," as well as tools allowing structural and magnetic characterization at the nanoscale. Most of these were already described within courses presented at the school.

I Intrinsic magnetic properties of matter

The basic concepts which explain 3d magnetism were clarified during the first part of the 20th century and those which explain 4f magnetism during the second half of this century. However, the magnetic energy terms constitute small terms with respect to those governing cohesion in the solid state and the quantitative description of the magnetic properties of matter remains very challenging. Today, using ab-initio calculations, the 0K magnetic properties of both 3d and 4f systems are progressively described quantitatively. However, the finite temperature properties are not yet well understood. In particular, the calculated value of the Curie temperature of 3d metals tends to be higher than the actual Curie temperature and the paramagnetic state is not well understood.

Recent interest has focussed on the understanding of impact of frustration on magnetic order. New states of matter emerge from these analysis, such as the spin liquid phase and the spin ice phase..

The discovery of ordered magnetic moments in Dilute Magnetic Semiconductors is a striking result which is presently attracting much attention. In systems such as (Ga-Mn)As, it is though that the interactions between Mn atoms are mediated by the holes. It is not yet clear whether the same mechanism explains the magnetic order in other dilute semiconductors, such as (Zn-Co)O.

Until very recently, it was though that ordered magnetic moments systematically involve 3d or 4f unpaired electrons. The recent claims that magnetic order above room temperature exist in systems such as CaB_6, HfO_2, thiol-coated Au or special forms of carbon have raised the question whether unpaired p electrons may be involved in the formation of ordered magnetic states. Assuming that these results are experimentally confirmed, their understanding will constitute one of the most challenging topics for magnetism research.

II Systems of reduced dimensions

The study of the magnetic properties of matter in small dimensions has constituted the main topic of magnetism research for the last ten years. Specific properties emerge in these systems because their dimensions are below the characteristic length-scales of magnetic interactions. Moment formation, exchange interactions and magnetic anisotropy are affected at very small dimensions, below typically 2 nm. Enhanced magnetic moment at surfaces is associated with electron higher localisation and high anisotropy is due to symmetry breaking. The mechanism by which coupling between magnetic layers is mediated via a non-magnetic layer is essentially understood. The understanding of finite temperature properties needs additional studies. In particular, the measurement of magnetic excitations in multilayers through inelastic neutron scattering would require high intensity of neutron beam which are not available in existing neutron reactor.

The properties of magnetic nanoparticules were less studied than those of multilayers. On the one hand, nanoparticle assemblies are intrinsically more complex than multilayers; on the other hand, it is more difficult to prepare model systems made of nanoparticles than made of multilayers. It results that the understanding of magnetic interactions and anisotropy in such systems are still at a preliminary stage. The properties of chemically-prepared magnetic clusters, have turned out to be very exciting, revealing original properties at the boarder between classical physics and quantum physics.

Other specific properties in nanoparticle systems include the giant Hall effects which appear in an assembly of nanoparticles close to the conditions for percolation. Similarly, the analysis of the dipolar interactions raises unexpected difficulties for a mechanism of which all essential bases are understood.

The domain wall width, δ, constitutes the characteristic length involved in magnetization processes. Magnetization processes in nanomaterials are thus affected at dimensions of this order of magnitude; this amounts to 3-5 nm is very high anisotropy systems and may reach 30-100 nm in low anisotropy soft magnetic materials. Original functional properties are found in nanomaterials below this size (see IV below).

One of the characteristic features of a given reversal process is the characteristic time associated with it. The study of time-dependent effects is a topic of high current interest, due to their high significance for the understanding of reversal processes and to their implication for magnetic recording applications. It is to be noted in particular that uniform reversal is much faster than nucleation-propagation and it tends to be favoured at small dimensions.

III Magnetism and transport

With the discovery of GMR in 1988, the study of the interplay between the magnetic properties and the transport properties of matter has become the main topic of magnetism research. In their basic principles, GMR and TMR are well understood and part of the research focuses on the preparation of systems showing the highest possible effects.

The controlled injection of a spin-polarised current between two media with different magnetic properties raises specific difficulties. This concerns the injection from a metal, a medium where the electron density is high but the mean free path is low to a semiconductor, where the electron density is low but the mean free path is large. In some other cases, such as the injection in manganite and similar systems, the origin of the electron depolarisation is not well understood.

Following a proposition due to Slonczewski and to Berger, the possibility to reverse magnetization under the effect of a spin-polarised current has been demonstrated. This has stimulated considerable recent interest.

The application of magneto-transport effects are in magnetic recording essentially. The possible development of MRAM's which would exploit the TMR effect is one of the most challenging possible future application of magnetic effects.

IV-Functional magnetic materials

Until recently, the development of new magnetic materials was essentially based on the discovery of new phases showing improved properties with respect to a given specific need.

In the near future, this research will become guided by the predictions emerging from material numerical modelling.

Assemblies of exchange-coupled magnetic nanograins constitute a new category of magnetic materials. As mentioned above, magnetization processes differ from those observed in usual magnetic systems because the grain size is of the order or below the characteristic dimension for reversal, itself defined by the domain wall width. A series of new magnetic materials exist which exploit this behaviour. This includes the ultra-soft nanostructured materials, the hard nanocomposites and the exchange-bias systems. The basic concepts at the origin of the behaviours observed in these systems are understood but there detailed description and understanding would require a quantitative structural characterization which the most modern tools (SEM, TEM, atom probe, near-field microscopies) do not permit yet.

Magnetic recording involves materials which associate exchange-decoupled nanoparticles. At present, the particle size approaches the superparamagnetic critical size. Various approaches are being tested to increase further the recording density by decreasing the grain size, while keeping a stable magnetic moment.

An additional large diversity of magnetic materials exists are related to other properties of interest for applications than the soft and hard properties described above. This includes the magnetostrictive materials, the magneto-caloric materials and the various multi-ferroic materials. In many of these, it is recognised that the properties of interest are intimately linked to the detailed nanostructure. However, the nature of this link itself is not understood very often.

V-High magnetic field generation

Traditionally, electromagnets were used for the generation of magnetic fields up to 2T and copper (Bitter or polyhelix) coils for field generation above 2T. With the discovery of the NdFeB high performance hard magnetic materials, an electrical machine which uses permanent magnets may have a smaller volume than its counterpart built with iron and copper coils. This explains the huge impact of these materials on the market of small high-performance electrical machines.

The technological development in mechanically resistive materials (high-strength polymers and carbon fibres) and the progress in electronics and numerical modelling have permitted a 45T hybrid magnets to be built in Tallahassee and various pulsed field set-ups to be developed. This trend will continue. Mini-coils could be built which would generate magnetic fields in excess of 50 T with a typical available energy of 1 kJ. These small energy systems involve limited financial investment. With the progress in data acquisition, experimental installation will be developed on this basis of which experimental possibilities will compete with the experimental possibilities offered by the hybrid magnets. Note that the transitory character of the thus-obtained magnetic field has interest in itself for the studies of time-dependent effects.

VI-Magnetic field and their applications

The term magnetoscience is often used when a magnetic field is used to modify or control a metallurgical or physical process. High-frequency magnetic fields influence the convection of liquid metals through the eddy currents created. They can be used to levitate diamagnetic materials. In metallurgy, their influence on the magnetic phase diagram of magnetic elements such as Fe, may permit specific microstructures to be obtained. The effect of magnetic fields, on the electrodeposition of both non-magnetic and magnetic materials, involves subtle effects which are not yet quantitatively understood.

Magnetic fields are suspected to influence the crystallization of calcite in water and that of wax formation in oil. Considering the number of convincing experimental reports, it is likely that the former of these effects at least is a real phenomenon, but no unambiguous interpretation of it has been proposed. Finally, magnetic fields have been reported to influence neurone activity but the reality of this effect requires confirmation.