Introduction

The European Science Foundation (ESF) is an independent, non-governmental organisation of national research organisations.
Our strength lies in the membership and in our ability to bring together the different domains of European science in order to meet the scientific challenges of the future. ESF's membership currently includes 77 influential national funding agencies, research-performing agencies and academies from 30 nations as its contributing members.
Since its establishment in 1974, ESF, which has its headquarters in Strasbourg with offices in Brussels and Ostend, has assembled a host of research organisations that span all disciplines of science in Europe, to create a common platform for cross-border cooperation.
We are dedicated to supporting our members in promoting science, scientific research and science policy across Europe. Through its activities and instruments ESF has made major contributions to science in a global context. The ESF covers the following scientific domains:
- **Humanities**
- **Life, Earth and Environmental Sciences**
- **Medical Sciences**
- **Physical and Engineering Sciences**
- **Social Sciences**
- **Marine Sciences**
- **Nuclear Physics**
- **Polar Sciences**
- **Radio Astronomy Frequencies**
- **Space Sciences**

Cover picture:
On the Kagome lattice, made out of corner sharing triangles, the ground state of antiferromagnetically coupled classical spins is not uniquely determined, as a result of frustration. Here a particular example is shown, where the red and blue spins on the hexagon can freely rotate without any energy cost, leading to a ground-state macroscopic degeneracy.

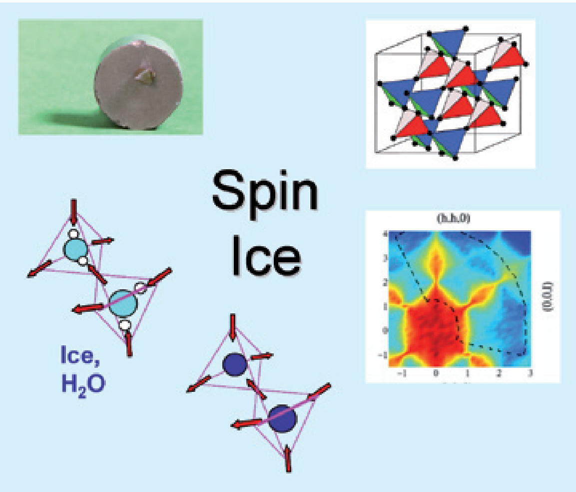
Frustration and degeneracy are at the heart of much important science, from protein folding to emergent electromagnetism, but reach their purest manifestation in magnetic materials. Highly Frustrated Magnetism (HFM) is a European network activity on the novel quantum states and effects in such materials. The field has grown during the last decade to incorporate the competition between various degrees of freedom (magnetic, charge, orbital, elastic) which leads to novel states and original effects in the presence of lattice frustration. These properties encompass spin liquids, orbital liquids and spin ice systems.

The interaction between the magnetic moments of localised electrons in insulating materials can lead to qualitatively new physical behaviour that originates in their complex cooperative behaviour. In geometrically frustrated systems, the lattice geometry prevents the spins from satisfying all the interactions between them, leading to exotic ground states like spin ice, highly entangled quantum spin liquids, orbital liquids and multipolar and nematic ordering in pure spin systems, as discovered in recent experimental and theoretical studies. Additionally, the role of lattice couplings and orbital degrees of freedom becomes emphasised in the process of lifting the degeneracy and selecting a ground state. The main goal of HFM is to reach a broad understanding of the important physical parameters that drive these new ground states.

This is an interdisciplinary research field: the synthesis and characterisation of new compounds and materials requires the latest materials science technology. The observation of new effects may require very sensitive experimental techniques, including extreme conditions and large-scale facilities. The theoretical understanding of the novel states requires new concepts and new methods.

ISIS muon spectrometer. The detectors (black) trace the positrons emitted after the desintegration of muons implanted in the studied materials. Magnetism can hence be explored at the atomic scale down to 40 mK.

Aims



Top left: crystal of spin ice, Ho2Ti2O7, stuck to the face of a magnet at room temperature.
Top right: crystal structure of spin ice – magnetic Holmium (Ho) ions occupy a lattice of corner-linked tetrahedra.
Bottom left: the analogy between water ice and spin ice – in water ice arrows locate hydrogens, in spin ice they represent atomic magnetic moments.
Bottom right: characteristic neutron scattering pattern of spin ice state where magnetic moments remain disordered down to zero temperature in the same way as the hydrogens in ice – both exceptions to the “Third Law” of thermodynamics.

Currently there are about 300 researchers involved in this project, from PhD students to senior scientists, belonging to teams from 14 countries. Rapid dissemination of the latest results, the smooth exchange of new ideas and interdisciplinary training is needed to maintain the engagement at a competitive level. European collaboration and exchanges should enable the best European groups to contribute to this field on an equal footing with Japanese and US scientists. Indeed, Europe will reach its full potential in this field only with cooperative application of theory, bulk measurements, NMR, synthesis, crystal growth and central facilities research (neutron and X-ray scattering. MuSR).

The HFM programme is a joint effort between solid-state chemists, experimental and theoretical physicists that provides a basis for the necessary training for interdisciplinary collaboration in this compelling frontier of condensed matter physics and materials science.

Operational activities of the programme consist in the organisation and support of conferences and workshops, a variety of visiting programmes and a long-term fellowship programme for young researchers.

The running period of the ESF HFM Research Networking Programme is for five years from May 2005 to May 2010.

The HFM programme provides the basis for the necessary interdisciplinary training and collaboration between material scientists and condensed matter experimentalists and theorists.

Developments in the materials science of synthesis techniques allows the design and production of new materials and molecules, as well as improving the purity of already existing compounds. In parallel with this, the refinement of experimental characterisation techniques has led to the discovery of exciting new phenomena in these materials. The explanations of such phenomena are a very stimulating challenge to theoreticians, leading to the emergence of new paradigms. However, this is not a one-way process, as the ideas and theories influence the synthesis, the choice and design of materials and stimulate new approaches.

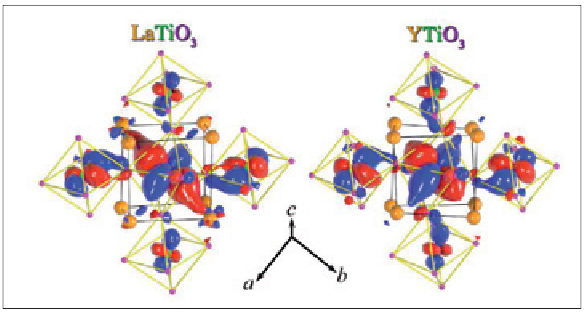
The specific scientific fields of the HFM are as follows:

1. Spin liquids.
Frustration of interactions has been thoroughly investigated theoretically in various geometries. Theory has been advanced ahead of experiments for a long time but recent developments and interest in frustrated lattices with classical and quantum spins by materials scientists modify this landscape. The gap between theory and experiment is closing. Specific experimental signatures are expected such as zero energy local modes, a huge density of excitations at T=0, singlet ground states, or a macroscopic degeneracy which might be relieved by any defect (the order by disorder scenario). One can cite corner-sharing magnetic lattices such as kagomé, pyrochlore lattices or square lattices with competing exchanges.

2. Macroscopic degeneracy.
The particularity of these highly frustrated lattice structures is that the ground state is macroscopically degenerate. In real materials, secondary interactions such as the dipole-dipole interaction in the case of rare-earth spin-ice compounds, or magneto-elastic couplings in the case of transition metal spinels, lift the degeneracy. Research in this field is twofold:

- Exploration of the ways the degeneracy is lifted in nature, and characterisation of the states.
- Investigations of degenerate phases, and classification of the orderings induced from the degenerate ground state manifold.

3. Orbital degrees of freedom.
In transition metal compounds with (almost) degenerate 3d orbitals, spin and orbital degrees of freedom occur with equal measure, and superexchange involves both of them. Frustration induced by interactions between orbital degrees of freedom can lead to interesting new



Probing orbital physics by LDA + DMFT calculation techniques. t_2g orbitals are represented in two transition metal oxides.

behaviour and to competition between different ordered and disordered (quantum liquid) states. The main examples of such behaviour can be found in transition metal spinel compounds.

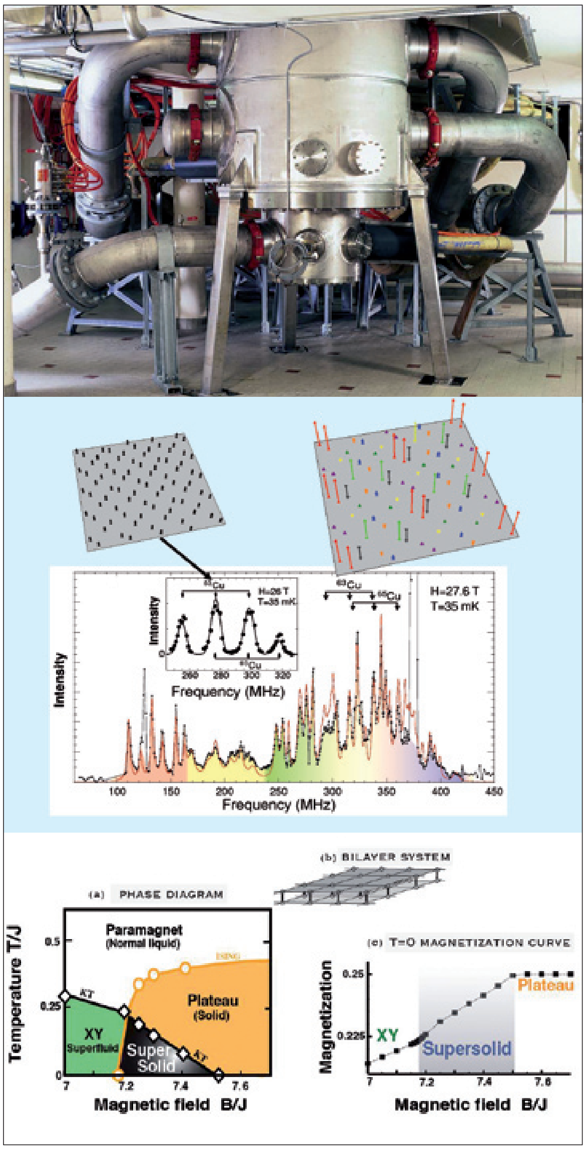
4. Non-magnetic ordering in spin systems.
Theoretical studies of some particular frustrated models has revealed the possibility of stabilising long range nematic, quadrupolar and multipolar order, where the order parameter is not the magnetisation (spin), but a more exotic quantity. Our aims are:

- Identifications of the main driving force behind non-magnetic orderings in spin models.
- Experimental search for materials showing nematic and quadrupole ordering.

5. Magnetisation plateaux and supersolid phases.
The magnetisation curve in some materials shows plateaux at some rational values of magnetisation as a function of the magnetic field. This is observed in triangular lattice systems, spin-ice compounds, $SrCu_2(BO_3)_2$, and in spinels. New developments include:

- Clarification of the mechanism behind plateaux formation which could involve boson condensation, supersolid phases in the vicinity of plateaux.
- Experimental search for new compounds showing magnetisation plateaux and supersolid phases.

6. Metallic spinels and pyrochlores.
In these systems with a non-integer number of electrons per ion, the short range Coulomb repulsion between nearest neighbour frustration influences not only the spin degrees of freedom, but also those associated with charge. Various behaviours have been observed, which can be influenced by frustration: metal-insulator transitions, superconductivity, anomalous Hall effect and heavy fermion-like behaviour. There is now a need for more compounds and physical studies. The aim is to understand the physics of these systems which could be at the border between the spin liquid and Fermi liquid states.



Exploring the Shastry-Sutherland model. Using the high field resistive magnet at the Grenoble High Magnetic Field Laboratory (top left), NMR spectra reveal the magnetic texture in the 1/8 plateau of the model compound $SrCu_2(BO_3)_2$ (top right).
Large scale Quantum Monte Carlo simulations for an antiferromagnetic spin-1/2 system defined on a simple bilayer geometry (b), as a model for the exploration of supersolid phases.
Bottom left: phase diagram. The various field/temperature-induced magnetic phases are described in a bosonic language: normal liquid, superfluid, solid, supersolid.
Bottom right: Zero temperature magnetization as a function of the field, highlighting the three types of ground states realized in this model.

HFM Activities

Programme management

Each participating country is represented on the Steering Committee which is typically held once a year either at a conference meeting or on request, if needed. Any person interested in our activities can join the HFM network at any time by contacting his country representative or the chairman of the network. We hope that new groups, starting to work in this field will join our programme during the five years.

Exchange of researchers

Exchange of researchers represents half of our budget. It is especially important that young scientists (PhD students and postdocs) can travel to various collaborative groups in order to achieve a more complete scientific expertise and/or to participate in various experimental work.

Financial support is threefold and detailed on the ESF website (**www.esf.org/hfm**). Priority will be given to scientists based in countries contributing to HFM (no deadlines for applications):

- short visit grants: fewer than 15 days. Fast response to the applicant
- exchange visit grants: from 15 days up to 6 months
- complementary support for travel to large-scale facilities in Europe: same rules as for short visit grants

Workshops

Different kinds of meetings can be organised:

- Focused workshops (about 20-30 participants – ~3 days). Planning of these workshops will depend on advances in our activities and does not require much administrative work. Every year two topical meetings could be organised on an *à la carte* basis.
- General workshops involving all groups (about 100 participants) with both invited and contributed talks (4-5 days), open to international contributions. This will be an opportunity to hold the Steering Committee meetings. Three large meetings could be organised during the 5 years of the project: kick-off, midterm, and final meeting. The kick-off meeting was organised in France in November 2005 and attracted 103 participants from 15 different nations.
- Sponsoring conferences held in the field of HFM.

School

A school was held in summer 2007.

Publication

A book issued based on the activities of the network will be written and edited.
More information at: **www.esf.org/hfm**

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For the latest information on this Research Networking Programme consult the HFM website:
www.esf.org/hfm

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