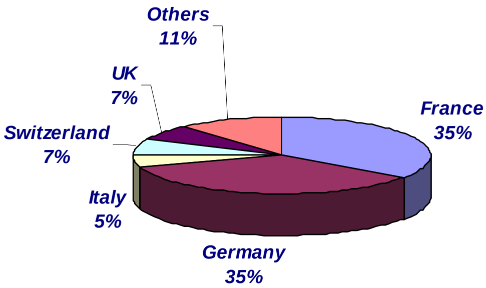
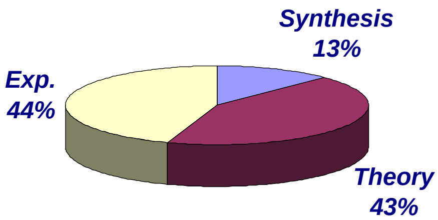
"HIGHLY FRUSTRATED MAGNETISM NETWORK" – midterm overview

Introduction

"Highly Frustrated Magnetism" (HFM) is a European network activity on the novel quantum states and effects in materials where frustration of interactions and macroscopic degeneracy play a leading role. The field has constantly been enlarged during the last decade and is still growing up to incorporate the competition between various degrees of freedom (magnetic, charge, orbital, elastic) which turn out to lead to novel states and original effects when lattice frustration is present. These encompass spin liquids, orbital liquids, spin ice systems.

Our HFM program represents a joint effort between solid-state chemists, experimental and theoretical physicists, and provides a basis for the necessary training for interdisciplinary collaboration in these compelling frontiers of condensed matter physics and materials science. It is our aim to stimulate existing collaborations and encourage new ones, as well as to participate to young researchers' training.





Our program was established in May 2005 for a 5 year duration. It gathers teams from 60-70 institutes interested in the field, from 14 countries all over Europe representing a roughly estimated total of 300 researchers, including post-doctoral fellows and PhD students. Note that our program is constantly open to new research groups and new countries keen to join. For example, Croatia joined our program during the first year.

The activities since the beginning of our network come out as initially proposed in our program: general conferences, specialized workshops, short visits and complementary support for travel expenses to large scale facilities, exchange visits, a school on Highly Frustrated Magnetism, the edition of an introductory book on HFM

The present report reviews the results of these various activities and is organized along the lines suggested by ESF.

Program scientific objectives

Our network is well represented in all the fields related to HFM, such as stated in our initial program, and noticeably leader in some of them, as reflected by the contributions to the International Conference on Highly Frustrated Magnetism held in Osaka in Aug. 2007 (Ratios of presentations by members of our ESF network: Plenary 2/4, Invited 8/18, Oral 13/28).
There are several focus activities strictly related to spin frustration and even more activities that connect aspects of competing interactions to other relevant degrees of freedom or functionalities in solids.
A general survey of our scientific activity is given below. In no case it is intended to be an extensive overview of the activity of each group of our network. Our activity is reflected by a selection of publications and further illustrated by a selection of 4 topics which highlight typical scientific achievements obtained within our 2 year activity.

Kagome-based lattices.

While the activity on volborthite and kagome bilayers has been pursued in the early days of our network, especially using NMR, neutron scattering or low-T magnetometry *(Edinburgh, Grenoble, Nantes, Orsay, Paris, Saclay, Toulouse)*, there was recently a burst of the activity in this field because of the surge of a novel Cu-based material (see Highlight 1) which could be the first realization of a perfect S=1/2 kagome network, then enabling at last to test experimentally more than 10 years of theoretical predictions on this fundamental topic of HFM. Many teams of our network now get involved and collaborate (*Braunschweig, Edinburgh, Grenoble, Orsay, Paris, Saclay, Technion, Toulouse*) both on the side of experiments and theory. Besides the already obtained results, we therefore expect worldwide achievements in the near future from our network.
Two new kagome-based systems were also discovered. In the langasite series, high quality large single crystals of Nd and Pr compounds could be grown mainly by the Czochralski method. The magnetic lattice of the Nd compound can be mapped to a kagome lattice with strong on-site anisotropy at variance with all existing cases (*Grenoble, Orsay and Braunschweig)*.
Single crystals of $Y_{0.5}Ca_{0.5}BaCo_4O_7$, a compound made of kagome layers of strongly coupled Co ions, were recently synthesized (*Braunschweig, Julich, Karlsruhe*). Diffuse polarized neutron scattering study revealed spin correlations in agreement with Monte Carlo simulations indicating a ground state with short range correlations and staggered chiral spin order.

Insulating pyrochlores and 3D corner sharing tetrahedral lattices.

At the beginning of our programme, this was already a very broad field of activity, with many facets both on the materials and physics sides. Rather than getting to some saturation level in this field, many remarkable advances and astonishing results have been produced in our network in the past two years which shows that it is still a vivid field of research.
- Among all pyrochlores $Tb_2Ti_2O_7$ was the only one known to retain the essential of a spin liquid behavior. Neutron scattering, μSR and specific heat experiments unexpectedly pointed at a very peculiar and completely different ground state when replacing Ti by Sn on the non-magnetic site, a short range ordered spin-ice with a high density of T=0 fluctuations (*Saclay, Grenoble, Orsay*). This compound participates to the challenge to theorists, who aim at understanding the subtle balance between dipolar interactions, exchange and anisotropy, hence the phase diagram of pyrochlores.
- Spin ice is a field where our network has played and keeps on playing a leading role (Highlight 2) at both theoretical and experimental levels. Magnetic field and magnetocaloric effects have been investigated experimentally and theoretically (*Kosice*, *London, Lyon, Oxford, Paris)*.
- Heisenberg pyrochlores: $Gd_2Ti_2O_7$ and $Gd_2Sn_2O_7$ have been investigated by several groups using neutron scattering, μSR and specific heat and theoretical interpretations have been proposed (*Grenoble, London, Saclay*)
- Relief of frustration: refined experiments such as diffraction under an applied field have been set up (Technion + SLS) to unravel the possible effects of a frustration-driven lattice distortion in $Y_2Mo_2O_7$, up to now only observed on spinel compounds. NMR work was also pursued (*Technion*).
- Weakly coupled tetrahedral $Cu_2Te_2O_5X_2$ (X=Cl, Br): work in this field combines theory and experiments in close collaboration with materials development. Excitations have been explored using Raman scattering, single crystal neutron diffraction on the $Cu_2Te_2O_5Cl_2$ revealed a new incommensurate structure, and detailed inspection of time-dependent effects was performed through magnetization experiments (*Braunschweig*, *Grenoble*, *ISIS, Lausanne*, *PSI*, *Warwick*, *Zagreb*).
Developing a synthesis concept for finding new compounds having low dimensional arrangements of transition metals is the route followed by the *Stockholm* group using lone pairs ions which yield weakly coupled tetrahedral systems. This group also collaborates with the *Lausanne*'s synthesis group to allow for a broader availability of large single crystals and different stoichiometries within the HFM network (*Augsburg*, *Braunschweig, Stuttgart, Zagreb*).

Metallic pyrochlores:

The mechanism and type of superconductivity in β-pyrochlores KOs_2O_6 and $RbOs_2O_6$ have been deduced from various measurements on high quality single crystals, including specific heat under 14 T, transport under high pressure, pointing to a strong coupling type of superconductivity and possible rattling of the K ions (*Lausanne, Zagreb, Zurich*).
The phase diagram of Mo based pyrochlores $R_2Mo_2O_7$ was studied using neutron diffraction and μSR either by varying pressure or by modifying the magnetic lattice through substitutions for R=Tb compound (*Saclay*). The phase boundary between the ferromagnetic metallic and insulating spin glass phases was investigated in collaboration with a Japanese team through IR spectroscopy, transport and thermodynamic measurements for R= Nd, Sm, Eu, Gd, Dy, and Ho (*Budapest*)

J1-J2 lattices:

This is one of the only cases of frustration induced by the geometry of interactions whih can be tackled experimentally with a good knowledge…of the interactions! In the vanadate family, a broad range of J1/J2 values could be explored either by changing the chemical composition or by tuning the exchange values using pressure as suggested by a recent combination of theoretical calculations and structure determinations (*Dresden*, *Magdeburg, Pavia*).

Spinels

In the vast family of spinels magnetic properties of $HgCr_2S_4$, $MnSc_2S_4$, $FeSc_2S_4$, MAl_2O_4, $GeCo_2O_4$, $GeNi_2O_4$ have been studied by groups of our network using thermodynamic measurements, Raman scattering and neutron scattering.
The interest in Cr-based spinels has been highlighted by a team of our network as well as that from ISSP, Japan and compounds such as $ZnCr_2S_4$, $HgCr_2S_4$ are model systems where to explore the coupling of spin degrees of freedom to the lattice, which yield spectacular phase transitions, magnetostriction effects and multiferroicity (*Augsburg, Grenoble)*
Some of the major results are described in Highlight n°3.
Ab-initio calculations about doping semiconducting non magnetic $ZnGa_2O_4$ by Fe have been performed in view of applications in the field of spintronics. (*Frankfurt*).
In transition metal spinels orbital degeneracy plays a big role and the intrication of spin and orbital degrees of freedom has been studied in several materials.

Triangular lattices

Since we started our program, there has been much revival in the domain of triangular lattices. The spin liquid behavior of $NiGa_2S_4$, discovered in Japan, triggered theoretical developments (*Budapest, Lausanne*) The complicated interaction paths might be at the origin of some ferro or antiferroquadrupolar order found in a S=1 Heisenberg model with bilinear and biquadratic exchange on the triangular lattice.
The Na cobaltates where superconductivity has been discovered in hydrated compounds in 2004, is also the focus of many groups in our network (*Braunschweig, Dresden, Kosice, Orsay, Stuttgart, Zurich*). Although frustration might not be the dominant ingredient, it is nevertheless an interesting case of doping in a triangular depleted lattice. It also triggered a renewal of the activity on parent Cr-compounds, $LiCrO_2$ and $NaCrO_2$ which had been little studied since the 70's and prove to be one of the unique representatives of the Heisenberg model on a triangular lattice (*Augsburg, Orsay*).
The organic compound κ-$(ET)_2Cu_2(CN)_3$ is a quite interesting triangular lattice Mott insulator. Most of the experimental work is made in Japan with a collaboration with the *Budapest* group for transport properties whereas structural studies have also been performed in the context of our program (*Braunschweig, Berlin, Dresden, Frankfurt, Stuttgart*).
Excitations on Cs_2CuCl_4 were also studied through neutron scattering but this system might rather prove to be dominated by 1D physics rather than a lattice of isoscele triangles (*Bristol*).

Magnetization plateaux, Bose-Einstein condensation and supersolid phases

The possible observation of a supersolid phase in $SrCu_2(BO_3)_2$ above the 1/8 plateau has renewed the interest on models of hard-core bosons with correlated hopping, the relevant type of effective model for frustrated arrangements of weakly coupled dimers (Highlight n° 4). Supersolid phases have been shown to be generic when correlated hopping is a significant source of kinetic energy, and the temperature properties of the supersolid phases have been investigated in details, revealing generically two phase transitions.
Bose-Einstein condensation of triplet excitations is found in the dimer system $BaCuSi_2O_6$, better known under the name "Han purple". It has been studied by NMR and EPR (*Frankfurt, Grenoble, Tallinn*).

Doping frustrated magnets

Although Na_xCoO_2 could have been viewed as an experimental realization for doping in a frustrated antiferromagnet, variational Monte Carlo simulations have proven that the superconductivity observed in the cobaltates is not simply a property of the t-J model on the triangular lattice. Several models with different types of valence bond solids have also been investigated away from half-filling, either at fractional fillings, in which case instabilities with a broken lattice symmetry have been identified, or at incommensurate filling, leading to spinon deconfinement (*Geneva, Lausanne, Toulouse*).

Theoretical approaches

In addition to theories directly related to experimental behaviors found on various systems and cited above, the theoretical investigation of several concepts has been pursued on the basis of minimal models. In particular, the concept of a quantum spin liquid has been further investigated in the context of projected variational wave functions (*Trieste*) and of quantum dimer models (*Lausanne, Trieste, Toulouse*). The variational approach has provided strong evidence in favour of a spin liquid with low-lying excitations, while the stability of the gapped Resonating Valence Bond phase, and the nature of the transition to the Valence Bond Solid phase have been determined with unprecedented accuracy using extensive Green's function Quantum Monte Carlo simulations. Observing these new states of matter in actual systems is one of the important challenges in the field.

Publications. 40-50 Letters (Phys. Rev. Lett, Europhysics Letters, Nature) and ca 100 articles (Phys. Rev. B, A or E, EPJB, Nature) have been published since May 2005.

- Two **broad audience papers** were published:

R. Moessner, A.P. Ramirez
Geometrical frustration
Physics Today, 59, 24-29 (2006)

S.T. Bramwell , News and Views, Nature 439, 273-274 (2006)

Some papers from our network

Quadrupolar Phases of the S=1 Bilinear-Biquadratic Heisenberg Model on the Triangular Lattice
A. Läuchli, F. Mila, and K. Penc
Phys. Rev. Lett. 97, 087205/1-4 (2006).

Quantum and Thermal Transitions Out of the Supersolid Phase of a 2D Quantum Antiferromagnet
Nicolas Laflorencie and Frédéric Mila

Phys. Rev. Lett. 99, 027202 (2007)

Dynamics of the quantum dimer model on the triangular lattice: Soft modes and local resonating valence-bond correlations
Arnaud Ralko, Michel Ferrero, Federico Becca, Dmitri Ivanov, and Frédéric Mila
Phys. Rev. B 74, 134301 (2006)

Incommensurate magnetic ordering in Cu2Te2O5X2 (X=Cl,Br) studied by single crystal neutron diffraction
O. Zaharko, H. Rønnow, J. Mesot, S. J. Crowe, D. McK. Paul, P. J. Brown, A. Daoud-Aladine, A. Meents, A. Wagner, M. Prester, and H. Berger
Phys. Rev. B 73, 064422 (2006)

Pinch Points and Kasteleyn Transitions in Kagome Ice
T. Fennell, S. T. Bramwell, D. F. McMorrow, P. Manuel.
Nature Physics 3 (no. 8) 566-573 (2007).

Ground states of a frustrated spin-1/2 antiferromagnet: Cs2CuCl4 in a magnetic field
Veillette MY, Chalker JT, Coldea R
Phys. Rev. B 71,214426 (2005)

Quest for Frustration Driven Distortion in Y2Mo2O7
E. Sagi, O. Ofer, A. Keren, J. S. Gardner
Phys. Rev. Lett. 94, 237202 (2005) .

Crystal structure and magnetic properties of FeTe2O5X (X=Cl, Br) – a layered compound with a new Te(IV) coordination polyhedron
R. Becker, M. Johnsson, R. K. Kremer, H-H. Klauss, and P. Lemmens
J. Am. Chem. Soc. 128 (2006) pp. 15469-15475.

Spin-Orbital Entanglement and Violation of Goodenough-Kanamori Rules
A.M. Oles, P. Horsch, L.F. Feiner, and G. Khaliullin
Phys. Rev. Lett. 96, 147205/1-4 (2006).

H., Magnetic ordering and ergodicity in the Cu2Te2O5X2 family of frustrated quantum magnets
Jagličić, Z.; Shawish, S. El.; Jeromen, A.; Bilušić, Ante; Smontara, Ana; Trontelj, Z.; Bonča, J.; Dolinšek, J.; Berger
Phys. Rev. B. 73 (2006)214408-1 - 214408-9.

Magnetocaloric study of spin relaxation in dipolar spin ice Dy2Ti2O7
M. Orendáč, J. Hanko, E. Čižmár, A. Orendáčová, M. Shirai, and S. T. Bramwell
Phys. Rev. B 75, 104425 (2007).

Colossal Magnetocapacitance and Colossal Magnetoresistance in HgCr2S4
S. Weber, P. Lunkenheimer, R. Fichtl, J. Hemberger, V. Tsurkan, and A. Loidl
Phys. Rev. Lett. 96, 157202 (2006)

Approaching the Ground State of the Kagomé Antiferromagnet
W. Schweika, M. Valldor, and P. Lemmens
Phys. Rev. Lett. 98, 067201 (2007)

Correlated Fermions on a Checkerboard Lattice
Frank Pollmann, Joseph J. Betouras, Kirill Shtengel, and Peter Fulde
Phys. Rev. Lett. 97, 170407 (2006)

Quantum J1-J2 Antiferromagnet on a Stacked Square Lattice: Influence of the Interlayer Coupling on the Ground-State Magnetic Ordering
D. Schmalfuß, R. Darradi, J. Richter, J. Schulenburg and D. Ihle
Phys. Rev. Lett. 97, 157201 (2006)

Quantum Kagomé Antiferromagnet in a Magnetic Field: Low-Lying Nonmagnetic Excitations versus Valence-Bond Crystal Order
D.C. Cabra, M.D. Grynberg, P.C.W. Holdsworth, A. Honecker, P. Pujol, J. Richter, D. Schmalfuß, J. Schulenburg
Phys. Rev. B71 (2005) 144420

Uniform and staggered magnetizations induced by Dzyaloshinskii-Moriya interactions in isolated and coupled spin-1 /2 dimers in a magnetic field
S. Miyahara, J.-B. Fouet, S. R. Manmana, R. M. Noack, H. Mayaffre, I. Sheikin, C. Berthier, and F. Mila
Phys. Rev. B 75, 184402/1-8 (2007).

Magnetic density of states at low energy in geometrically frustrated systems
A. Yaouanc, P. Dalmas de R\\'eotier, V. Glazkov, C. Marin, P. Bonville, J.A. Hodges, P.C.M. Gubbens, S. Sakarya, C. Baines
Physical Review Letters 95 (2005) 047203 (1-4)

Single-ion anisotropy in the gadolinium pyrochlores studied by an electron paramagnetic resonance
V. N. Glazkov, M. E. Zhitomirsky, A. I. Smirnov, H.-A. Krug von Nidda, A. Loidl, C. Marin, and J. P. Sanchez
Phys. Rev. B 72, 020409(R) (2005).

Ordering in the pyrochlore antiferromagnet due to Dzyaloshinsky-Moriya interactions;
M. Elhajal, B. Canals, R. Sunyer, C. Lacroix
Phys. Rev. B 71, 094420 (2005)

Unconventional Continuous Phase Transition in a Three-Dimensional Dimer Model
Fabien Alet, Grégoire Misguich, Vincent Pasquier, Roderich Moessner and Jesper Lykke Jacobsen
Phys. Rev. Lett. 97, 030403 (2006)

Phase separation and flux quantization in the doped quantum dimer model on the square and triangular lattices
A. Ralko, F. Mila, D. Poilblanc
Phys. Rev. Lett. 99, 127202 (2007)

Nematic order in square lattice frustrated antiferromagnets
N. Shannon, T. Momoi, P. Sindzingre
Phys. Rev. Lett. 96, 027213 (2006)

Quantum Magnetism in the Paratacamite Family: Towards an Ideal Kagome Lattice
P. Mendels, F. Bert, M. A. de Vries, A. Olariu, A. Harrison, F. Duc, J. C. Trombe, J. S. Lord, A. Amato, and C. Baines
Phys. Rev. Lett. 98, 077204 (2007)

Ordered spin ice state and spin fluctuations in Tb2Sn2O7.
I. Mirebeau, A. Apetrei, J. Rodriguez-Carvajal , P. Bonville, A. Forget, D. Colson, V. Glazkov, J. P. Sanchez, O. Isnard, E. Suard
Physical Review Letters. 94, 246402, (2005).

Quantum dimer models and effective Hamiltonians on the pyrochlore lattice

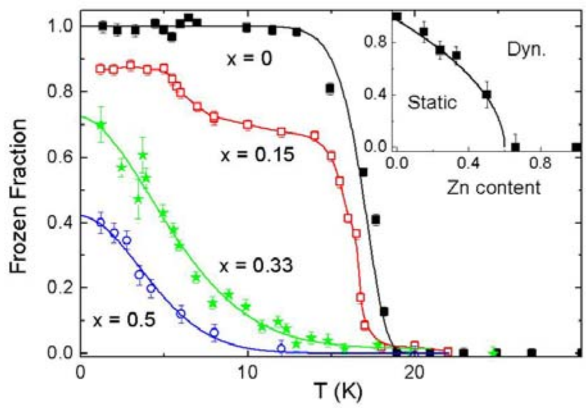
R. Moessner, S.L. Sondhi, M.-O.Goerbig,
Phys. Rev. B 73, 094430 (2006)

A novel candidate for an exotic spin liquid state:
Herbertsmithite, a "perfect" S=1/2 kagome compound

(Orsay + Edinburgh + Technion + Braunschweig + Toulouse + Saclay)

The fundamentals of Highly Frustrated Magnetism trace back to the 70's when Fazekas and Anderson proposed that triangular-based antiferromagnets might stabilize a resonating valence bond ground state rather than a magnetic Néel state. This concept of a “spin liquid” ground state built on the resonance of singlets has been seminal for many theoretical investigations, including on high temperature superconductors. Frustration, quantum fluctuations and corner sharing geometry of the magnetic lattice have been further recognized as the main ingredients favouring the stabilization of a RVB state, which triggered intense theoretical studies of the S=1/2 kagome antiferrromagnet and led to various proposals finally not restricted to a RVB state. Yet, the various theoretical predictions could not be properly tested up to now since an experimental realization combining these three ingredients was crucially missing.

A new synthetic material $Cu_3Zn(OH)_6Cl_2$, a close relative of a mineral compound discovered in a Chilean mine in 2004 and based on spin triangles forming a kagome network, could well be the very first realization of this novel state. Soon after the publication of the first synthesis in US, it could be reproduced by two teams of our network and was studied intensively through a broad panel of techniques. Using the high sensitivity of muon spin rotation, we could probe the sub-Kelvin magnetic properties and were the first to demonstrate the absence of any magnetic ordering down to 50mK, our lowest experimental temperature well below the J ~ 200K coupling energy of the spins [1]. NMR experiments indicate that down to J/150, excitations could be gapless [2]. Substitutional defects have however been further revealed using neutron scattering and specific heat [3] and are at the heart of present investigations using Raman scattering and low-T SQUID or High Field measurements [4]. Finally ^{17}O NMR allows to probe directly the kagome susceptibility and no singlet-triplet gap is observed [5]. This field is rapidly growing up both on the theory and the experiment sides and our network is at the forefront of research on this material, combining synthesis, state of the art experiments and theoretical interpretations [6].



Phase diagram of the paratacamite family compounds $Cu_{4-x}Zn_x(OH)_6Cl_2$. Magnetic order vanishes as the perfect kagome case (x=1) is approached.

[1] P.Mendels, F. Bert, M.A. de Vries, A. Olariu, A. Harrison, F. Duc, J.C. Trombe, J.S. Lord, A. Amato and C. Baines, Phys. Rev. Lett. 98, 07204 (2007)
[2] O. Ofer, A. Keren, E.A. Nytko, M.P. Shores, B.M. Barlett, D.G. Nocera, C. Baines and A.Amato, cond-mat/061054;
[3] M.A. de Vries, K.V. Kamenev, W.A. Kockelmann, J. Sanchez-Benitez and A. Harrison, cond-mat/07050654
[4] F. Bert, S. Nakamae, F. Ladieu, D. Lhote, P. Bonville, F. Duc, J.C. Trombe and P. Mendels., submitted to Phys. Rev. B (2007)
[5] A. Olariu, P. Mendels, F. Bert, F. Duc, J.C. Trombe, M.A de Vries and A. Harrison, submitted to Nature Physics (2007)
[6] G. Misguich and P. Sindzingre, cond-mat/07041017, submitted to EPJB (2007)

The Kasteleyn transition in spin-ice; experiment and theory

(London, Lyon, Oxford, Paris)

In spin ice materials like Ho_2Ti2O_7 and $Dy_2Ti_2O_7$ [1] the Ising-like rare earth spins are analogous to hydrogen displacement vectors in water ice. Spin ice shares with water ice the Pauling "zero point" entropy and shows several interesting properties in applied magnetic field, including liquid-gas type transitions and a giant entropy spike (see, for example [2]). In general, the spin ice phenomenology arises from a balance of exchange and dipolar couplings. The additional influence of an external field alters this balance, leading to a very subtle and complicated phase diagram.

A recent development in spin ice physics has been the discovery of a very special type of phase transition called a Kasteleyn transition, in which the system crosses from a state with finite entropy to a state with zero entropy as a function of temperature or applied field. Such phase transitions have been known in `toy' models of magnetism for many years but have never before been realized in a real magnet. They are considered to be of importance in biological systems, for instance in the behaviour of lipid bilayers, as well as many other physical systems [4].

The potential of spin ice materials to show Kasteleyn transitions was first realized by Moessner (Paris and Oxford) and colleagues [5] who demonstrated a recipe for observing a two dimensional Kasteleyn transition in a field slightly tilted away from the [111] crystallographic direction. This was confirmed experimentally by Fennell and colleagues (London) on $Ho_2Ti_2O_7$, and published in *Nature Physics* [6]: see Fig. 1.

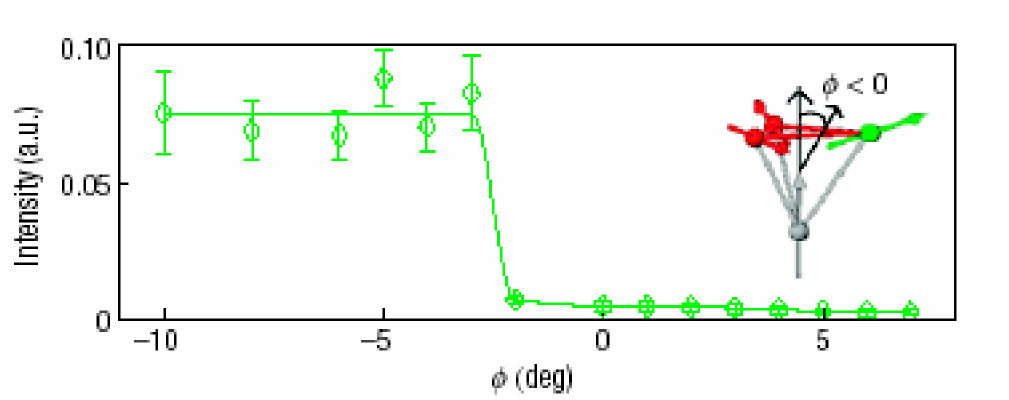
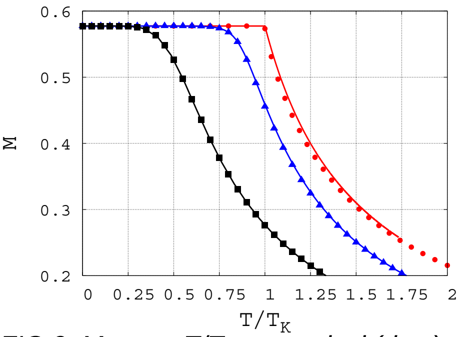


FIG. 1: The abrupt change in neutron scattering intensity with a small field tilt that signals the two dimensional Kasteleyn transition in $Ho_2Ti_2O_7$ (from Ref. 5).

A more recent HFM supported project was the visit of Holdsworth and Jaubert (Lyon) to Oxford to interact with Moessner and Chalker in early 2007. During this time they calculated that a field applied along the [100] direction gives a three dimensional Kasteleyn transition [7]. A high precision Monte Carlo algorithm was used, with non-local spin dynamics, as well as analytical calculations on a Cayley tree. The transition is signalled by a discontinuity in the slope of the magnetization M versus temperature plot, as shown in Fig.2 where data are shown for M *vs* T/T_K, where T_K is the Kasteleyn temperature. There is overwhelming evidence for a three dimensional Kasteleyn transition in the limit $h \Rightarrow 0$. For larger fields the discontinuity is rounded and the saturation occurs at a lower temperature with respect to $T_K(h)$. As seen in Fig. 1, the analytic results fall very close to the simulation data [6].

Spin ice materials offer the possibility for the study of the above transition. Field scans have been performed at fixed low temperature in holmium titanate [8]. In figure 2 the simulation data for M *vs* B is compared with that for Holmium Titanate at $T=1.2$ K. The agreement is good, providing strong evidence that the transition could be more closely approached in future experiments.



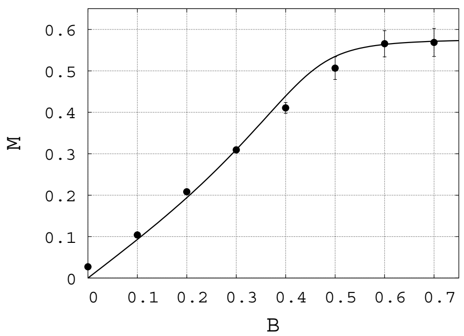


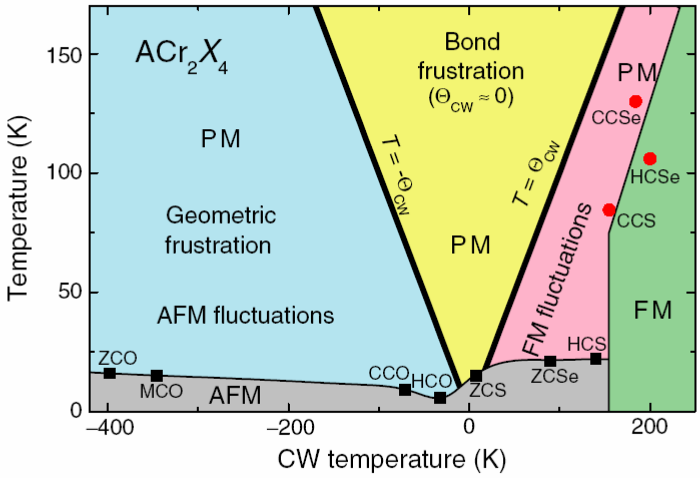
FIG 2. $M_{[100]}$ vs T/T_K: numerical (dots) and analytic (lines) for h/J=0.01, 0.4 and 1 from right to left.
FIG 3. M_z vs B; analytic (line) and experiment (dots) for $Ho_2Ti_2O_7$ at T=1.2K [12]

[1] S. T. Bramwell and M. J. P. Gingras, *Science* **16**, 1495 (2001).
[2] R. Moessner and S. L.Sondhi, *Phys. Rev. B* **68** 064411 (2003).
[3] Taguchi et al., *Science* **291**, 2573 (2001).
[4] J. F. Nagle, Phys. Rev. Lett, 34 1150 (1975).
[5] R. Moessner and S. L. Sondhi, Phys. Rev. B 68, 064411 (2003).
[6] T. Fennell, S. T. Bramwell, D. F. McMorrow, P. Manuel,and A. Wildes, Nature Physics 3, 566 (2007).
[7] L. D. C. Jaubert, J.T. Chalker, P.C.W. Holdsworth and R. Moessner, in preparation, (2007).
[8] T. Fennell, O. A. Pentrenko, B. Fak, J. S. Garnder, S. T. Bramwell, and B. Ouladdiat, Phys. Rev. B 78, 224411
(2005).

Competing interactions and colossal response to external fields in spinels

(Augsburg + Braunschweig + Grenoble)

The spinel structure AB_2X_4 with magnetic ions on the A or B site is a family of compounds that show an enormous variety of physical properties and allows studying both fundamental as well as application relevant questions. Metal-Insulator transitions with orbital degrees of freedom ($CuIr_2S_4$), superconductivity ($CuRh_2S_4$), long range ferromagnetic ($CdCr_2S_4$,) and antiferromagnetic ($FeSc_2S_4$, $MnSc_2S_4$) correlations are observed. The primary magnetic properties of the spinels are governed by the occupation of the two different sites. Magnetic ions at the A-site of spinels form a diamond lattice and are subject to strong frustration. For $MnSc_2S_4$ the onset of long range magnetic order is shifted to low temperatures with a complex ordering process [1, 2] as studied by neutron scattering and thermodynamic experiments. The low temperature phase is related to a spiral spin liquid with significant order by disorder as suggested by L. Balents and co-workers [3]. Similar behaviour has recently been found in aluminate spinels MAl_2O_4 (M = Mn; Fe, Co) speaking in favour of a more general property of such frustrated diamond lattices. Spinels with magnetic ions on the B sites have a non-frustrated magnetic subsystem. However, also here a complex interplay of competing degrees of freedom may exist leading to colossal response to dielectric polarization and local lattice displacements. In ferromagnetic $CdCr_2S_4$ a very large magnetocapacitive effect has been observed in proximity to the ferromagnetic ordering temperature [4]. Structural degrees of freedom are involved in this process as shown by Raman scattering and anomalies in the lattice constant. In $HgCr_2S_4$ that is closer to the boundary between ferromagnetic and antiferromagnetic ground states these multiferroic effects are even more pronounced [5]. This allows us to study systematically the interplay of phonons with the spin system and establish a bond frustrated state for the latter and especially for $ZnCr_2S_4$ [6] as shown in the figure below.



Schematic magnetic phase diagram of ACr_2X_4 with characteristic temperatures plotted versus the Curie-Weiss temperature, FM (red circles) and AFM (black squares) ordering temperatures. Thin solid lines separate ordered from paramagnetic phases [7].

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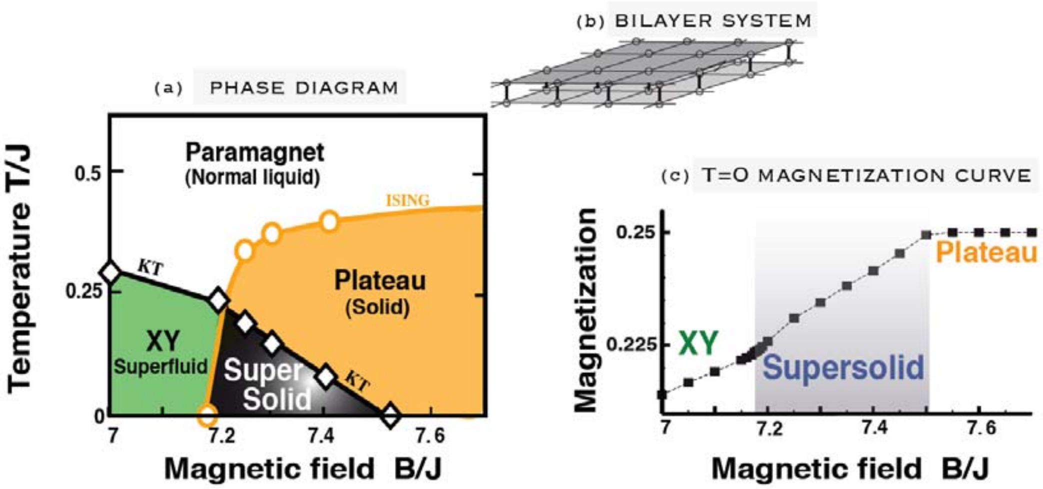
Supersolid Phases in Frustrated Antiferromagnets
(Grenoble, Lausanne)

Understanding the magnetization plateaux that have been observed in a few frustrated magnets, in particular $SrCu_2(BO_3)_2$, has been a very active field of research. This culminated in 2002 with the identification of the magnetization profile inside the 1/8 plateau of $SrCu_2(BO_3)_2$ by NMR experiments in 28 T and at 35 mK [1]. Three, in principle unrelated advances, have recently boosted this field. First, the possible observation of a supersolid phase of Helium 4 has reopened the search for supersolid phases and has put this issue at the forefront of current research [2]. Secondly, in the context of cold atoms, the possibility to stabilize such a phase for lattice models of hard core bosons has been definitely established [3]. Thirdly, in a collaboration involving several members of the network, the observation of a persistent broken translational symmetry above the 1/8 plateau of $SrCu_2(BO_3)_2$ has been interpreted as a possible equivalent of a supersolid phase, and has demonstrated that frustrated quantum magnets were among the best candidates to observe such a phase [4]. Since then, a huge theoretical effort to find such phases in models of frustrated quantum magnets and to characterize their properties has taken place. It has recently been established that such a phase should undergo two separate phase transitions upon raising the temperature, one at which the transverse ordering (the equivalent of the superfluidity) disappears, and one at which the longitunal spin density wave (the solid component of the supersolid) disappears [5]. Progress in identifying physically relevant models of frustrated magnets in which a supersolid phase can be expected is going on worldwide at an impressive pace [6].



"Large scale Quantum Monte Carlo results for an antiferromagnetic spin-1/2 system defined on a bilayer geometry. a) Phase diagram. The various field/temperature-induced magnetic phases are described in a bosonic language: normal liquid, superfluid, solid, supersolid. The magnetic analog of a supersolid state of hard-core bosons can be stabilized at the edge of a magnetization plateau. The critical lines belong to different universality classes (KT, Ising), as indicated on the plot. b) Geometry of the bilayer. c) Zero temperature magnetization as a function of the field, highlighting the three types of ground states realized in this model."

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2. Assessments of results achieved to-date

We give below a brief summary of our activities

Workshops: We are on-line with the initial plan of our program (2 workshops/year with 30 – 40 participants and one general workshop with 80 – 100 participants every 18 months) and even beyond our initial objectives in terms of participation. The school was held inTrieste this summer. All these events were extremely successful! Many of these events were co-funded by another institution and gathered our community with others (Trieste, Leiden).

- La Londe (Nov. 2005), C. Lacroix and P. Mendels: kick-off meeting, 2.5 days, 102 participants from 15 countries, 58 institutes represented. It was the kick-off meeting of our ESF program "Highly Frustrated Magnetism". Besides the scientific part which dominated the meeting, the aim and objectives as well as the possible actions within our program were presented in detail, so as to stimulate an active enrolment of the participants in the network. General introductory talks were given for each selected topic, High field, pyrochlores, kagomé, orbital degeneracy, low-dimensional, triangular, two-dimensional. Recent results covering the activities of the various groups participating to the program were reviewed as well as to-date open problems, emerging new theoretical concepts, synthesis approaches which were all obviously at the heart of our objectives and future progress in the field. The objectives of the meeting were reached, i.e. gathering a sizeable fraction of the European researchers in the field of frustrated magnetism, covering most of the institutes /research teams and spreading the information about our network in a friendly atmosphere and a high international level of science.

- Lyon (March 2006)- + *CECAM* -,P. Pujol, D. Cabra, F. Mila : "Novel theoretical aspects of frustrated spin systems", 2.5 days, 36 participants. 75% of the participants came from France, Germany and Switzerland, there were also participants coming from Argentina, Croatia, Hungary, Italy and the United Kindom. The workshop brought together theorists working on the problem of frustrated magnetism from very different perspectives and using many different but at the same time complementary techniques. The exchanges took place at a very high level and provided an excellent opportunity for theorists to establish common priorities and clarify the current state of the art.

- Stockholm (June 2006), M. Johnsson and P. Lemmens: "Competing Interactions: Material Aspects", 2.5 days, 26 participants. The organizers brought together a mix of young scientists at the level of PhD students and postdocs together with senior researchers. Different preparation techniques, synthesis strategies, crystal growth techniques, characterization and spectroscopy were represented in the scientific program with an emphasis on novel materials and developments. The workshop gave a good overview over the most important materials currently studied within the field of HFM and was important for the specialists in the different synthesis techniques for learning more on advantages and drawbacks of different synthesis techniques/crystal growth techniques.

- Dresden (January 2007) + *MPI-PKS* –P. Fulde, Z. Hiroi, P. Lemmens, R. Moessner: "Mobile Fermions and Bosons on Frustrated Lattices" , 3.5 days, 96 participants. The topic 'frustrated systems with itinerant aspects' was divided into several subtopics that where represented by key speakers in addition to posters. These were: cobaltates, triangular organics, itinerant pyrochlores, spinels, frustration and ordering, quantum criticality, bosons and supersolids, fundamental mechanisms, checkerboard physics. Material science, modelling as well as theoretical aspects were discussed.

- Trieste (July-August 2007) + *ICTP* – F. Mila, F. Becca, J. Essler, A. Tsvelik: " School and Workshop on Highly Frustrated Magnets and Strongly Correlated Systems: From Non-Perturbative Approaches to Experiments", 8+ 8 days, 220 participants. The school provided an introduction to the field of Highly Frustrated Magnetism to over 100 students, a large proportion from European countries participating to the HFM program. It was organized around basic courses covering the fundamentals (theory, experiments, materials) and advanced lectures dealing with more specialized aspects of the problem. The workshop was mostly about frustrated magnets but included as well three sessions on one-dimensional problems. It brought together international experts from the US, Canada, Japan and several European countries to discuss the latest theoretical and experimental findings in all aspects of the field.

- Leiden (Sept 2007) + *Lorentz Center* R. Moessner, I. Block, W. Hofstetter and K?. Schoutens: "Disorder in Condensed Matter and Cold Atoms", 5 days, 40 (?) participants.

Details about each of these workshops are available in the reports on the ESF website.

Short visits: 23 applications, 20 accepted, 15 PhD students or post-docs. The three rejected were conference support (2) and outside of the field (1, related to magnetic multilayers). All applications were of excellent quality and related to novel projects in the field of HFM, in relation with very active teams or highly ranked proposals in large scale facilities.

Exchange visits: 4 applications, 4 accepted, 3 PhD students, average visit time 3 months.

School: Last summer in Trieste, very successful, 110 students, 35 students supported by ESF, co-funded by ICTP, 25 students coming from third-world countries.

Book : As planned in our program, a book "Introduction to Frustrated Magnetism" will be edited by our network. The content of the book was discussed at the steering committee, in close relationship with the school program , last year in Paris, and authors for each chapter were contacted under the responsibility of C. Lacroix, P. Mendels and F. Mila . All chapters are due on 15th October and the book should be finished by the end of this year. The book will be published as a volume of “Springer series in solid state Sciences”

Six parts:
- Basic concepts in frustrated magnetism
- Probing frustrated magnets
- Frustrated systems
- Specific effects in frustrated magnets
- Advanced Theoretical Methods in Frustrated Magnetism
- Related topics

To summarize, the exchange within our program have been at a quite high international level. Both visits and workshops have enabled at very different levels to initiate new collaborations between teams of different countries or to strengthen existing ones. Presentations of results at workshops where many teams as well as worldwide leaders enable to review on a frequent basis novel trends in the field of HFM and are the source of many challenging discussions which appear as the best warranty of deep thoughts in our field of research. Workshops lead the three communities, theorists, experimental physicists and material scientists to better understand each other, which was one of the declared goals of our network. Up to now, exchange visits have remained at a marginal level and the members of our network seem to prefer workshops as a means of exchange which indeed occurs on a larger scale than individual visits.

Up to now, all workshops have been indeed overbooked. The time devoted to free discussions in these workshops has been constantly increased during the first two years of activity of our network.