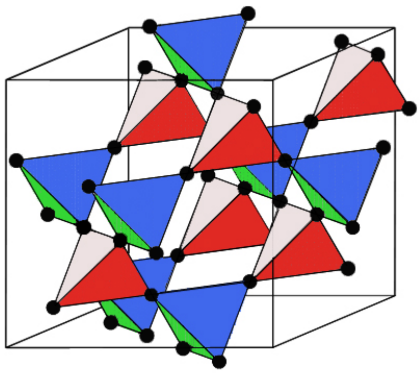
Scientific Report on "Topics In the Frustration of Pyrochlore Magnets"

An ESF-HFM Workshop
held he Cosenor's House, Abingdon
16th-18th September 2009



Organised by Steve Bramwell (LCN) and Sean Giblin (ISIS)

Summary

The workshop was held in Abingdon, U. K. over three days, with registration after lunch on the first day and departure after lunch on the third day. Accommodation, meals and conference facilities were all provided on site at Cosener's House, an attractive ancient manor house on the banks of the River Thames, with extensive lawns. The idyllic setting made for an excellent scientific atmosphere and many delegates expresses their approval of the venue.

The 45 Delegates came from 8 European countries and also from 3 countries in North and South America. Countries represented were U.K., France, Germany, Italy, Sweden, Israel, Slovakia, Germany, USA, Canada, Argentina. For a relatively small meeting, there was a truly international flavour. Most delegates were experimental physicists, but there was also a significant number of eminent theoreticians and a few chemists. There were 8 Ph. D. students out of the 45 delegates, 23 invited speakers, 3 contributed talks. There was a poster session on the first evening with 13 posters presented.

All delegates had accommodation and meals paid for. Invited speakers from Europe were reimbursed travel within reasonable limits. A contribution was made to the travel of 4 American invited speakers. Others had business in Europe and were only paid local travel expenses. The invitation of leading American researchers was considered very important, as the field is based there (see below).

The first day was dominated by discussions of spin liquids and other highly frustrated pyrochlore antiferromagnets. The highlight of the second day was a long session on "spin ice", which certainly represented the most eminent group of spin ice researchers ever assembled in a single place. This was particularly exciting because work discussed at the meeting led a month later to three papers in *Nature* and *Science*, that grabbed the news headlines. While most of the discussion was about frustrated spin ice materials, there was an excellent session on artificial spin ice micromagnetic arrays, a new route to magnetic frustration. The third day returned to pyrochlore antiferromagnets and the session finished with a short discussion on kagome antiferromagnets, looking forward to the forthcoming ESF workshop on kagome systems.

In general there was much lively scientific discussion and debate. There was plenty of time for this after the talks and in tea and coffee breaks. Many new contacts were made and experiments were set up. A particularly successful outcome was the opportunity for the European researchers to meet the eminent North American researchers who were invited. This particular sub-field of highly frustrated magnetism is centred more in the USA and Canada than in Europe, so it was an excellent opportunity to "seed" European research in the area. The special focus on spin ice was also a success. Recent events have shown major new opportunities in this area, and many wills see the genesis of the field as being the ESF Workshop at the Cosener's House.

Scientific Content and Discussion

Session 1 was entitled "Spin Liquid Dynamics" and was led off by Prof. Seunghun Lee, University of Virginia, discussing his work on emergent excitations and the relief of frustration by complex ordering processes in chromium based spinel materials. There followed a theory talk by Prof. John Chalker, University of Oxford, that described the calculation of the dynamical structure factor of such systems, and finally another experimental talk by Dr. Ross Stewart, ISIS, describing neutron scattering work on the itinerant frustrated system, beta-manganese.

Session 2 was focused on "Spin Liquid Phase Diagrams" and began with an experimental neutron investigation, by Dr. Pascale Deen, ILL, into the magnetic field dependence of the highly frustrated $Gd_3Ga_5O_{12}$ garnet, highlighting the interplay between spin liquid and long range interactions. There followed a theoretical discussion of the effect of constrained bond disorder on the ground state of the pyrochlore lattice by Dr. Simon Banks, University of Oxford.

The evening poster session allowed for scientific discussion over drinks and nibbles.

The poster titles are listed below:

Bob Aldus, UCL, Stuffed Spin Ice.
Joseph Betouras, University of St Andrews, First- order versus unconventional phase transitions in three-dimensional dimer models.
Peter Conlon, Univeristy of Oxford, Hexagon Modes arising in Heisenberg Pryochlore Antiferromagnets.
Rodolfo Borzi, Experiments and Numerical simulations on $Dy_2Ti_2O_7$ with H//[111].
Adam Harman-Clarke, UCL, Topological Constraints in Kagome Ice
Sarah Dunsigner, FRM-II, High field MuSR Studies of $Dy_2Ti_2O_7$.
Tom Hayes, University of Warwick, Geometric Frustration in Lanthanide Salts $SrLn_2O\text{-}_4$
Ludovic Jaubert, University of Lyon, Spin ice under uniaxial pressure: influence of the topological constraints.
Bastian Klemke, Helmholtz Center, Thermal Properties of $Dy_2Ti_2O_7$ at Low Temperatures and Magnetic Fields up to 2 T.
Jonathon Morris, Helmholtz Center, Diffuse Scattering.
Alzbeta Orendacova, Kosice, Slow spin relaxation in dipolar spin ice.
Giacomo Prando, Univeristy of Pavia, Dilution effects in Ho_{2-x}YxSn2O7: From the spin ice to the single-ion magnet;
Stuart Calder, UCL, Rare earth preovskites with the frustrated fcc lattice

Session 3 focused on "Spin Glasses and Planar Pyrochlores". Prof. Amit Keren, Technion, described an experimental investigation into the $Y_2Mo_2O_7$ puzzle attempting to describe why most pyrochlore lattices partially freeze. This talk was followed by a theoretical description of phase transitions in pyrochlores by Prof. Bruce Gaulin, McMaster. Another theoretical talk followed by Prof. Michel Gingras, Waterloo, who discussed how the spin hamiltonian of an XY ferromagnet can be used to fit paramagnetic neutron scattering data. Finally in this session Martin Orendáč, Kosice, described how he has used the magnetocaloric effect to characterise the slow relaxation in dipolar spin ice.

Session 4 was dedicated to Orbital and Transport Effects beginning with a theoretical description of spin orbit effects on the Mott transition in frustrated pyrochlores, by Prof. Leon Balents, UCSB, as spin orbit coupling can have dramatic effect on the band structure. An experimental description of anomlaous phonons and Hall effect in pyrochlores was then given by Prof. R. Suryanarayanan, Université Paris-Sud.

Session 5 was entitled to "Spin Ice Theory" and focused on topolgical features which have similar properties to magnetic monopoles. Dr. Claudio Castelnovo, University of Oxford, started by describing manifestations of monopoles physics which can be described by elementary excitations and be used to define to time scales in spin ice. This was followed directly by Prof. Roderich Moessner, Dresden, who discussed the manifestions of monopole phyiscs, in particular by investigating the diffusion annihilation process in quenched spin ice and suggesting possible experiments to test his theory. Finally Prof. Peter Holdsworth, ENS Lyon, described a theory of diffusive monopole physics motivated by experimental measurements.

Session 6 described "Spin Ice Experiments" and began with an experimental investigation of Dirac like strings in $Dy_2Ti_2O_7$ using diffuse neutron scattering in high magnetic fields by Prof. Alan Tennant, Helmholtz Center. Dr. Santiago Grigera from St Andrews University then described detailed magnetic measurements on $Dy_2Ti_2O_7$ focusing on non-equilibrium effects and instabilities in the magnetisation. Another diffuse neutron investigation into spin ice materials by Dr. Tom Fennell. ILL, demonstrated the presence of ice rule defects in the scattering data supporting the picture of magnetic monopoles. Finally Prof. Steve Bramwell, LCN-UCL, presented a mehod to measure magnetic charge in spin ice mateirals and then demonstrated experimentally that the charges do indeed act via Coulombs law.

Session 7 was dedicated to "Artifical Spin Ice". This began with the arcitect of this field, Prof. Peter Schiffer, Penn State, describing his teams discovery of magnetic frustration in interacting nanomagnet arrays that describes the 2-in-2-out spin configuraiton of spin ice materials. This talk was followed by an experimetnal observation of magnetic monopole defects in an artifical kagome spin ice system by Dr. William Branford, Imperial College.

Session 8 focused on the "Terbium pyrochlores" . Prof. Isabelle Mirebeau, Laboratoire Léon Brillouin, described her pioneering work on subjecting materials like $Tb_2Ti_2O_7$ to high pressure, and a unique neutron method to measure the components $\chi_{//}$,$\chi_{\perp}$ of the local susceptibility tensor. Dr. Paul McClarty, Waterloo, described theoretical progress in finding an an effective Hamiltonian for $Tb_2Ti_2O_7$ and describing the frustration in terms of quantum crystal field fluctuations. Dr. Ben Ueland, NIST, described the system $Tb_{2+x}Ti_{2-2x}Nb_xO_7$, which includes spin liquid, spin glass and ordered behaviour.

Session 9 was concerned with new frustrated systems. Dr. Oleg Petrenko, University of Warwick, described recent on SrEr2O4, containing triangles and hexagons, and particularly neutron diffuse scattering studies that may be compared to those of the pyrochlore systems discussed elsewhere. Dr. Pascal Manuel, ISIS, similarly presented diffuse scattering maps of the kagome-like system $YBaCo_4O_7$ Showing evidence of a spin liquid state. Finally Dr. Andrew Wills, UCL, described his chemical synthesis and studies of the new kagome systems Kapellasite, Haydeeite and Fe3Sn2, a frustrated ferromagnetic metal. This was a fitting way to end the meeting as the next HFM workshop is on kagome systems.

Assessment of the results and impact of the event on the future direction of the field

The event proved to be an important networking exercise for the field of highly frustrated pyrochlore magnetism.

The focus on spin ice was very timely: weeks after the meeting, three papers presented there were published in *Nature* and *Science* and caused a huge media interest across the world, one of the biggest stories in physics for many years. It is clear that the field of spin ice has been rejuvenated by the discovery of magnetic monopoles and magnetricity, and the chance for the leading researchers in this area to meet and discuss was very valuable. Similarly, the presentation of new work on artificial spin ice brought this area to the attention of many delegates for the first time.

A second impact was in the area of pyrochlore spin liquids. It is clear that significant progress is now being made in understanding “emergent clusters” and other dynamical aspects of the problem such as quantum crystal field fluctuations. The meeting provided an excellent chance for workers to share ideas in these areas, which should bring the field forward in the long term.

A third impact was related to the role of neutron scattering. This was not only a very good series of talks on frustrated magnetism but also a very useful series on neutron scattering techniques. It was very clear that there has been huge progress in the practical ability to measure reciprocal space maps, which is the key to a real understanding of macroscopically degenerate states in frustrated magnetism. It is likely that theoreticians and experimentalists alike will take note of these developments and focus their research in the knowledge that such maps are now routinely measurable. Hence the meeting served a useful purpose in advertising the new techniques.

A final impact was in bringing to the attention of the community a number of relatively new concepts, such as topological insulators, and new systems such as the frustrated kagome ferromagnet. These concepts and systems promise to inform the future directions of research into highly frustrated magnetic materials.

SCHEDULE FOR HFM WORKSHOP

Wednesday 16th Sept	12:00-12:45	ARRIVAL
	12:45	LUNCH
	14:00	INTRODUCTION
Session 1: Spin liquid dynamics	14:20-14:45	Lee
	14:45-15:10	Chalker
	15:10-15:35	Stewart
	15:35-16:10	TEA
Session 2: Spin liquid phase diagrams	16:10-16:35	Deen
	16:35-17:00	Banks
Poster Session	18:00-19:00	DRINKS/POSTERS
	19:30	DINNER
Thursday 17th Sept		
Session 3: Spin glass and planar pyrochlores	09:00-09:25	Keren
	09:25-09:50	Gaulin
	09:50-10:15	Gingras
	10:15-10:40	Orendac
	10:40-11:10	COFFEE
Session 4: Orbital and transport effects	11:10-11:35	Balents
	11:35-12.00	Suryanarayanan
	12:30-13:30	LUNCH
Session 5: Spin Ice theory	13:45-14:10	Castelnovo
	14:10-14:35	Moessner
	14:35-15:00	Holdsworth
	15:00-15:30	TEA
Session: 6: Spin Ice experiment	15:30-15:55	Tennant
	15:55-16:20	Grigera
	16:20-16:45	Fennell
	16:45-17:10	Bramwell
	17:10-17:40	TEA
Session 7: Artificial Spin Ice	17:40-18:05	Schiffer
	18:05-18:30	Branford
	19:30	DINNER
Friday 18th Sept		
Session 8: Terbium pyrochlores	09:00-09:25	Mirebeau
	09:25-09:50	McClarty
	09:50-10:15	Ueland
	10:15-10:45	COFFEE
Session 9: New frustrated systems	10:45-11:10	Petrenko
	11:10-11:35	Manuel
	11:35-12:00	Wills
	12:00-12:30	CLOSE
	12:30	LUNCH

ABSTRACTS FOR TALKS

Session 1: Spin Liquid Dynamics

1.1 Seunghun Lee, University of Virginia

Frustrated magnetism and cooperative phase transitions in Cr-based spinels

The Cr-based spinel crystal system, ACr_2O_4 has been fertile ground in studying the effects of magnetic frustration. The experimental findings, with primary focus on neutron and synchrotron x-ray scattering techniques, are hereby reviewed. Highlighted are novel collective phenomena, such as the zero-energy excitation mode in the spin liquid phase, zero-field and field-induced novel phase transitions, and the emergence of complex local spin entities. Such a diversity in the exotic properties stems from their close proximity to critical points among degenerate states and a delicate balance between spin and lattice degrees of freedom.

1.2 John Chalker, University of Oxford

Spin dynamics in pyrochlore antiferromagnets

We study the low temperature dynamics of the classical Heisenberg antiferromagnet with nearest neighbour interactions on the pyrochlore lattice. We present extensive results for the wavevector and frequency dependence of the dynamical structure factor, obtained from simulations of the precessional dynamics. We also construct a solvable stochastic model for dynamics with conserved magnetisation, which accurately reproduces most features of the precessional results. Spin correlations relax at a rate independent of wavevector and proportional to temperature.

P. H. Conlon and J. T. Chalker, Phys. Rev. Lett. 102, 237206 (2009).

1.3 Ross Stewart, ISIS

Magnetic structure and dynamics of beta-magnanese

Beta-manganese metal is an example of a geometrically frustrated nearly antiferromagnetic metal on the verge of moment localisation. It's unique crystal structure, and proximity to a Stoner critical point leads to some fascinating magnetic short-range ordered spin structures, and spin-dynamical properties (non-Fermi-liquid scaling). A survey of these properties will be presented for pure beta-Mn and various dilute alloys. Recently, and for the first time, our group as grown large (2 cm^3) single crystals of beta-Mn(Co), and we present the result of neutron polarization analysis studies of the magnetic short-range ordered structure of these crystals, as well as inelastic neutron scattering studies of the non-exponential spin-dynamics.

Session 2: Spin Liquid Phase Diagrams

2.1. Pascale Deen, ILL

Probing the magnetic field dependence of the spin liquid phase in the highly frustrated $Gd_3Ga_5O_{12}$ garnet.

Frustration of antiferromagnetic interactions has been singled out as adominant ingredient in the quest for novel quantum states. GGG is an ideal candidate since the Gd ions are located on two interpenetrating corner sharing triangular sublattices, necessary for magnetic frustration. No sign of long range order has been observed down to 25 mK in zero external applied field despite a Curie-Weiss temperature of 2 K. Early studies indicated that the ground state is not a simple spin glass but a mixture of a spin liquid with a set of rigid magnetic pieces nucleated around impurity centers; however, complex long range order is induced by an applied magnetic field. I shall present polarised neutron diffraction and inelastic neutron spectroscopy results that clarify a long standing question about the interplay between spin liquid order and a complex long range magnetic order which is necessary to produce frustration in GGG.

2.2 Simon Banks, Oxford and UCL

The effect of constrained random bond disorder on the ground state configurations of Heisenberg spins on the pyrochlore lattice

Recent neutron scattering experiments (Fennell *et al.*) have sharpened the picture of an algebraic spin liquid phase in $CsNiCrF_6$, originally proposed by Zinkin et al. (1997). Anderson famously predicted that systems such as this, with equal numbers of two magnetic species populating a pyrochlore lattice, should favour configurations with two of each type of ion present on every tetrahedron. With this in mind, we have studied a simple model of a system comprised of equal numbers of two species of Heisenberg spins, A and B, distributed randomly across a pyrochlore lattice, but subject to the ice-rules like constraint that each tetrahedron has two A and two B type spins. We have characterized the ground state magnetic behaviour for all possible combinations of the three exchange interactions governing the system. This reveals a large region of exchange parameter space for which the system is in a spin liquid like state consisting of a soup of single species, non-interacting, antiferromagnetic loops. This configuration is robust even in the presence of four ferromagnetic bonds per tetrahedron. We demonstrate that the highly constrained form of quenched disorder imposed on the ion placement removes the possibility of a spin glass transition from this cooperative paramagnetic regime. We go on to discuss how the underlying structural configuration leads to algebraic magnetic correlations, manifested in the familiar bow-tie structure factor.

Session 3: Spin Glass and Planar Pyrochlores

3.1. Amit Keren, Technion

The $Y_2Mo_2O_7$ puzzle

Standard degeneracy-lifting mechanisms of thermal or quantum fluctuation do not remove the ground state degeneracy of the pyrochlore lattice. Yet, with only one exception of $Tb_2Ti_2O_7$ all pyrochlores freeze, at least partially. In some cases magneto-elastic coupling might be responsible for the degeneracy removal; the lattice distorts to relieve the frustrated interactions. However, lattice distortions and symmetry changes as a function of temperature are a common feature in solids, even without magnetic interactions. Therefore, it is not yet clear whether: (I) the magnetic interactions drive the distortion; or (II) the distortion takes place because of electrostatic (chemical) interactions, and the magnetic properties, such as freezing, follow. To address these issues, field dependent experiments can be performed to hopefully elucidate the spin Hamiltonian.

In my talk I will present four different experiments: (I) ^{89}Y NMR, (II) Transverse field (TF) μSR, (III) Field-dependent high resolution x-ray powder diffraction, and (IV) Field-dependent neutrons diffraction. I will then review what we do understand and what we don't.

3.2 Bruce Gaulin, McMaster

Phase Transitions in Planar Pyrochlores

I will (mostly) discuss new neutron scattering work on two magnetic pyrochlores Er_2Ti_2O7 and $Yb_2Ti_2O_7$, which can be thought of in terms of XY magnetic moments decorating a network of corner-sharing tetrahedra. The ferromagnet, $Yb_2Ti_2O_7$, displays a disordered ground state, but can be brought to order in an applied magnetic field. The antiferromagnet, $Er_2Ti_2O_7$, displays a long range ordered state at low temperatures which can be driven into a quantum disordered state by application of a magnetic field.

3.3 Michel Gingras, Waterloo

$A_2B_2O_7$ Pyrochlore Medley: Spin Hamiltonian of the $Yb_2Ti_2O_7$ XY Ferromagnet and Spin Glass Freezing in a Weak Random Bond Model of $Y_2Mo_2O_7$

My talk will consist of two parts. In the first one, I will review the paradoxical phenomena exhibited by the $Yb_2Ti_2O_7$ pyrochlore XY ferromagnet, emphasizing the peculiar nature of the paramagnetic diffuse neutron pattern. I will explain how we used mean-field theory and/or random phase approximation to describe (fit) the paramagnetic neutron scattering of $Yb_2Ti_2O_7$ and determine, fairly precisely, a unique set for the values of all symmetry-allowed nearest-neighbor bilinear exchange interactions in that material. In the second part, I will report results from our extensive Monte Carlo studies of a weak random-bond classical Heisenberg pyrochlore antiferromagnet, the study of which was motivated by the spin glass freezing in the stoichiometric $Y_2Mo_2O_7$ pyrochlore antiferromagnet compound. I will emphasize that our results suggest a thermodynamic spin glass transition in the model considered that is best described by a combined spin and chiral transition very similar to that found in the three-dimensional Edwards-Anderson Heisenberg spin glass model.

Session 3b: Relaxation in spin ice

3b.4 Martin Orendáč, Kosice

Slow spin relaxation in dipolar spin ice

Spin relaxation in dipolar spin ices $Dy_2Ti_2O_7$, $Ho_2Ti_2O_7$, and XY antiferromagnet $Er_2Ti_2O_7$,was investigated using magnetocaloric effect and susceptibility. Adiabatic demagnetization of $Dy_2Ti_2O_7$, at temperatures where the orientation of spins is governed by 'ice rules' ($T < T_{ice}$) confirmed thermally activated relaxation, however, the resulting temperature dependence of the relaxation time reveals faster relaxation than anticipated by mere extrapolation of the corresponding high - temperature data. The faster relaxation was also suggested by the thermal response of $Dy_2Ti_2O_7$, on small pulses of a magnetic field.

Susceptibility study of $Ho_2Ti_2O_7$, were performed at $T > T_{ice}$ and high magnetic fields and indicate slow relaxation of spins analogous to that reported in highly polarized cooperative paramagnet [2]. Similar behavior found in $Er_2Ti_2O_7$, and even in a non - frustrated system $Gd_2(fum)_3$ $(H_2O)_4.3H_2O$ may suggest alternative mechanism based on a resonant phonon trapping.

Session 4: Orbital and Transport Effects

4. 1 Leon Balents, UCSB

Spin-orbit effects on the Mott transition in frustrated pyrochlores

Recent theory and experiment have revealed that strong spin-orbit coupling can have dramatic qualitative effects on the band structure of weakly interacting solids. Indeed, it leads to a distinct phase of matter, the topological band insulator. In this paper, we consider the combined effects of spin-orbit coupling and strong electron correlation, and show that the former has both quantitative and qualitative effects upon the correlation-driven Mott transition. As a specific example we take Ir-based pyrochlores, where the subsystem of Ir 5d electrons is known to undergo a Mott transition. At weak electron-electron interaction, we predict that Ir electrons are in a metallic phase at weak spin-orbit interaction, and in a topological band insulator phase at strong spin-orbit interaction. Very generally, we show that increasing strength of the electron-electron interaction, the effective spin-orbit coupling is enhanced, increasing the domain of the topological band insulator. Furthermore, in our model, we argue that with increasing interactions, the topological band insulator is transformed into a ``topological Mott insulator'' phase, which is characterized by gapless surface spin-only excitations. The full phase diagram also includes a narrow region of gapless Mott insulator with a spinon Fermi surface, and a magnetically ordered state at still larger electron-electron interaction.

4. 2 R. Suryanarayanan, Université Paris-Sud

Anomalous phonons and Anomalous Hall effect in Pyrochlores

We have investigated temperature dependent Raman spectra of $R_2Ti_2O_7$ (R Sm, Gd, Tb, Ho, Dy) single crystals. In general, we find an anomalous behaviour of phonons. The non-magnetic $Lu_2Ti_2O_7$ also shows similar behaviour. We attribute this to phonon –phonon anharmonicity. Further, replacing Ti by Zr (non-magnetic elements) has a dramatic effect on the magnetic properties of Sm-ions in the two compounds – $Sm_2Zr_2O_7$ seems to be more frustrated than $Sm_2Ti_2O_7$. A new phonon mode appears in $Dy_2Ti_2O_7$ below 110 K with a concomitant contraction of the cubic unit cell volume. Further, experiments on O^{18} substituted $Dy_2Ti_2O_7$ confirm the phonon origin of the new mode. In addition, our Raman and X-ray data on $Tb_2Ti_2O_7$ indicate a subtle structural deformation at 9 Gpa. By carefully controlling the valence state of Mo, we have grown single crystals of $Sm_2Mo_2O_7$. We have observed fingerprints of ordered spin-ice state in this compound. We will present detailed studies of Anomalous Hall effect in this compound.

Session 5: Spin Ice Theory

5.1 Claudio Castelnovo, Oxford

Manifestations of monopole physics

The low temperature phase in spin ice materials such as DTO and HTO appears to be characterised by an emergent rather than broken (gauge) symmetry, and in a rare instance of fractionalisation in three dimensions, the elementary excitations are point-like objects with the character of magnetic monopoles. The peculiar nature of these excitations leads to unique signatures in the equilibrium and response properties of these materials. We review several of these properties, and we show how one can develop a theoretical understanding using knowledge and techniques from the field of Coulomb liquids. In particular, we identify two distinct time scales in spin-ice: a short one pertaining to the defect density (and therefore the energy), and a long one to the spin correlations.

5.2 Roderich Moessner, Dresden

Thermal quenches in spin ice

We study the diffusion annihilation process which occurs when spin ice is quenched from a high temperature paramagnetic phase deep into the spin ice regime, where the excitations – magnetic monopoles – are sparse. We find that due to the Coulomb interaction between the monopoles, a dynamical arrest occurs, in which 'nonuniversal' lattice-scale constraints impede the complete decay of charge fluctuations. This phenomenon is outside the reach of universal mean-field theory for a two-component Coulomb liquid. We identify the relevant timescales for the dynamical arrest and propose an experiment for detecting monopoles and their dynamics in spin ice based on this non-equilibrium phenomenon.

5.3 Peter Holdsworth, ENS Lyon

The stochastic dynamics of magnetic monopoles and Dirac strings in spin ice

Model spin ice shows the remarkable property of fractionalization of magneticmoments into effective magnetic monopoles. The development of experimental signatures of the presence of monopoles is hence one of the most engaging and exciting challenges of condensed matter physics. In this talk I will present a theory of diffusive monopole dynamics, motivated by dynamic measurements on both Holmium and Dysprosium Titanate. I will show that the relaxation rate of the underlying Dirac string network is in quantitative agreement with magnetic relaxation times measured for $Dy_2Ti_2O_7$, providing an explanation for the non-standard nature of spin freezing observed in spin ice compounds and giving strong evidence for the presence

of monopoles in these materials. [Jaubert and Holdsworth, Nature Physics 5, 258 - 261 (2009)]
Session 6: Spin Ice Experiment

6.1 Alan Tennant, HMI Berlin

Strings and applied fields in $Dy_2Ti_2O_7$

The spin ice state is argued to be well-described by networks of aligned dipoles resembling solenoidal tubes. We demonstrate, by diffuse neutron scattering, the presence of such strings in the spin-ice $Dy_2Ti_2O_7$. This is achieved by applying a symmetry-breaking magnetic field with which we can manipulate density and orientation of the strings. In turn, heat capacity is described by a gas of end states interacting via a magnetic Coulomb interaction.

6.2 Santiago Grigera, St. Andrews

Non-equilibrium effects, instabilities, and intermediate phase in $Dy_2Ti_2O_7$ with H / / [111]

We have studied the magnetisation process in $Dy_2Ti_2O_7$ at low temperatures with field applied along [111] using magnetisation and susceptibility probes. Our work can be divided into two parts: the study of the magnetisation process from the spin-ice to the kagome-ice phase and the transition between the Kagome-ice plateau and full polarisation.

Below 600 mK and at very low fields, the system shows marked non-equilibrium effects, characterised by the appearance of jumps in the low field magnetisation. We found that their occurrence and particularities depend dramatically on the field sweep rate. A careful study allowed us to determine a region beyond which the system becomes unstable, developing cascade-like steps in magnetisation.

The second issue of interest is the metamagnetic "dimer to monomer" transition at very low temperatures. Using magnetisation and very sensitive magnetic susceptibility measurements, we observe that, contrary to theoretical predictions and current interpretation of the experiments, this transition occurs in two stages. We find magnetic signatures for two transitions, which coincide with signatures in the specific heat. This implies the existence of an intermediate phase which we attribute to long range, long period order induced by dipolar interactions.

6.3 Tom Fennell, ILL

Polarized neutron scattering studies of Holmium and Dysprosium Titanate.

Recent experiments on spin ices using polarized neutron scattering have revealed the pinch point scattering characteristic of dipolar or ice rule spin correlations. Such scattering has been strongly anticipated in theories of spin ice but not previously observed in the zero field state. The scattering compares well with simple ice rule models, but there is are extra contributions implying a modification of the pure ice rule constraint. I will discuss this comparison and its implication for the theory of projective equivalence. Finally the effects of ice rule defects are clearly visible in the data, I will illustrate how their behaviour supports the picture of magnetic monopoles in spin ice.

6.4 Steve Bramwell, LCN- UCL

Measurement of the charge and current of magnetic monopoles in spin ice

We present a method by which magnetic charge can be measured without recourse to a material-specific theory. We apply the method to spin ice ($Dy_2Ti_2O_7$) to prove that this material contains magnetic charges that interact via Coulomb's law and are accelerated by a magnetic field. We observe magnetic monopole current, characterise deviations from Ohm's law, and measure the absolute value of the monopole charge.

Session 7 Artificial Spin Ice

7. 1 Peter Schiffer Pennsylvania State University

Magnetic frustration of interacting nanomagnet arrays

Our group has developed and studied 'artificial geometrically frustrated magnets' which provide model systems to study a range of magnetic phenomena. These systems consist of arrays of lithographically fabricated single-domain ferromagnetic islands, arranged in different geometries such that the magnetostatic interactions between the island moments are frustrated. Magnetic force microscopy imaging of these arrays allows us to study the accommodation of frustration through the local correlations between the moments as a function of both the strength of the interactions and the geometry of the frustration. We have also used these arrays to analyze the process of demagnetization, which is necessary to access low energy collective states in our arrays and in many other magnetic systems. Our results shed light on the nature of magnetism in patterned arrays and correspondingly demonstrate that artificial frustrated magnets can provide a rich new arena in which to study the physics of frustration with direct analogies to the pyrochlore systems.

7.2 William Branford, Imperial College

Observation of magnetic monopole defects in an artificial kagome spin-ice system

Recent predictions suggest that in the frustrated magnetic system known as kagomé spin ice, magnetic properties can be fractionalised to a unit defined as a magnetic charge and that such charge obeys a magnetic analogue of Coulomb's law. In such a system it is thought that one might form mobile quantum topological defects associated with such magnetic charges, and that these can be considered to be "monopole defects". Using magnetic force microscopy, and a specific type of magnetic field history, we show that in an artificial spin ice Cobalt honeycomb nanostructure the magnetic charge order can be imaged directly and the motion of monopole defects can be tracked, allowing direct study of the breakdown of the Ice rules. In contrast to the bulk spin ices there is bound magnetic charge at each vertex. This local magnetic charge distribution creates a trapping potential, pinning the monopole defects to a single site until additional field is applied. We demonstrate that monopoles of opposite sign are observed to hop in opposite directions in an applied field, producing a magnetic charge, or monopole current and creating head-tail dipole strings analogous to Dirac's strings.

Session 8 Terbium Pyrochlores

8.1 Isabelle Mirebeau, Laboratoire Léon Brillouin

Terbium pyrochlores: new questions and new challenges

Rare earth pyrochlore $R_2T_2O_7$ provide text book examples of geometrically frustrated magnets. Among them, Terbium compounds are especially intriguing owing to the specific Tb crystal field with low energy excited doublet, and to first neighbour effective interactions which can easily switch from ferro to antiferromagnetic. $Tb_2Ti_2O_7$ is considered as a spin liquid or "quantum spin ice", whereas $Tb_2Sn_2O_7$ with larger lattice constant behaves as a "soft" or ordered spin ice. Neutron diffraction under extreme conditions such as very low temperatures, high pressures or high magnetic fields, as well as polarized neutrons provide an original insight on these compounds, which may in some cases be extended to other pyrochlores. I will discuss the following questions. What happens to a soft spin ice when you compress it? Can it turn back to a spin liquid? How does it compare to the model spin ice $Ho_2Ti_2O_7$? We performed a neutron diffraction study of $Tb_2Sn_2O_7$ under high pressure of 5 GPa and down to 60 mK [1]. What is high field ground state of the $Tb_2Ti_2O_7$ spin liquid? Recent results of a high field single crystal study will be shown up to 12 T and down to 40 mK. We investigated the stability of the k= (001) field induced phase for several field orientations along <110>, <111> and <112> axes, as well as the possible existence of a magnetization plateau (H//<111>). What are the precursor effects of the ground state in the paramagnetic phase? Using polarised neutron diffraction, we studied the field induced magnetic structures in $R_2Ti_2O_7$ single crystals with either uniaxial (R=Tb, Ho) or planar (R=Er, Yb) anisotropy [2,3]. This is the unique method to determine the components $\chi_{//}$,$\chi_{\perp}$ of the local susceptibility tensor, relative to the <111> trigonal axis. Its determination provides a universal description of the field induced phases in a large temperature (2-270 K) and field range (1-7T) whatever the field direction. Comparison of the thermal variations of $\chi_{//}$ and $\chi_{\perp}$ with calculations using the rare earth crystal field shows that exchange and dipolar interactions must be taken into account. We determined the molecular field tensor in each case and show that it is strongly anisotropic. This might be an important point to consider for theory.

8.2 Paul McClarty, Waterloo

Towards an effective Hamiltonian for $Tb_2Ti_2O_7$

Terbium titanate, $Tb_2Ti_2O_7$ is a frustrated magnetic material in which no sign of long-range magnetic order has been observed down to 50 mK although the Curie-Weiss temperature is -14 K. Instead one finds that short-range correlations develop below about 20 K. Quantum fluctuations involving excited crystal field levels have been shown to be significant in this material but their effect on spin correlations has not been studied. We address this problem using an effective Hamiltonian which includes the effects of quantum fluctuations perturbatively. The correlations are studied by computing the classical ground states of this model. The classical phase diagrams allow us to see how the physics of spin ice is connected to the possible physics of $Tb_2Ti_2O_7$ as the crystal field ground-to-first excited gap is tuned. In addition to the familiar classical dipolar spin ice model phases, we see a stabilization of a q=0 ordered ice phase over a large part of the phase diagram - ferromagnetic correlations being preferred by quantum corrections in spite of an antiferromagnetic coupling in the microscopic model. Frustration is hence seen to arise from quantum crystal field fluctuations in a model for $Tb_2Ti_2O_7$

8.3 Ben Ueland, NIST

Coexisting Magnetic Order and Cooperative Paramagnetism in the Stuffed Pyrochlore $Tb_{2+x}Ti_{2-2x}Nb_xO_7$.

Neutron scattering and magnetization measurements have been performed on the stuffed pyrochlore system $Tb_{2+x}Ti_{2-2x}Nb_xO_7$. We find that despite the introduction of chemical disorder and increasingly antiferromagnetic interactions, a spin glass transition does not occur for $T \geq 1.5$ K and cooperative paramagnetic behavior exists for all x. For $x = 1$, Tb_3NbO_7, an antiferromagnetically ordered state coexisting with cooperative paramagnetic behavior is seen without applying any external fields or pressure, a situation advantageous for studying this unique cooperative behavior.

Session 9 New Frustrated Systems

9.1 Oleg Petrenko, University of Warwick

$SrEr_2O_4$ in an applied magnetic field – a quantum phase transition?

$SrEr_2O_4$ belongs to a family of materials with the formula $SrLn_2O_4$, where Ln = Gd, Dy, Ho, Er, Tm and Yb. In these compounds the magnetic Ln ions are linked through a network of triangles and hexagons [1]. Despite the strong exchange interaction (CW . −12 K), long range ordering develops in $SrEr_2O_4$ only at 0.75 K [2]. The structure consists of FM chains running along the c axis, two adjacent chains being stacked antiferromagnetically. The moments point along the c direction, but only one of the two Er sites has a sizeable moment of 4.5 μB. We have recently grown high quality single crystals of several compounds from the $SrLn_2O4$ family, including $SrEr_2O_4$. An unusual behaviour in this compound is observed in an applied field, where for Hk c axis, a field of 0.5 T completely destroys long range magnetic order and introduces instead some sort of state with short range magnetic correlations. This conclusion is reached on the basis of neutron diffraction experiment at ISIS, where a replacement of the sharp Bragg peaks by broad diffuse scattering features is observed. A further increase in magnetic field causes a restoration of the long range order and a disappearance of the diffuse scattering. These observations resemble the behaviour seen around a quantum critical phase transition, although additional investigations are required to prove the presence of a QCP in $SrEr_2O_4$.

9.2 Pascal Manuel, ISIS

Magnetic correlations in the extended kagome system $YBaCo_4O_7$

We present a study of the frustrated system $YBaCo_4O_7$ above the Neel temperature by means of single crystal neutron scattering. The observed magnetic diffuse scattering is successfully modeled by direct Monte Carlo simulations. A quasi–1D order is obserbed along the c-axis whereas a spin-spin correlation function in the kagome layers (ab plane) is found to be rapidly decaying, a feature typical of spin liquids. $YBaCo_4O_7$ experimentally realizes a new class of two-dimensional frustrated systems where the strong out-of-plane coupling does not lift the in-plane degeneracy, but instead acts as an external ‘‘field.’’

9.3 Andrew Wills, UCL Chemistry

Some new frustrations with kagome magnets

This talk introduces some new experimental kagome systems, namely Kapellasite, Haydeeite and Fe_3Sn_2. The first two of these are examples of S=1/2 quantum magnets and are closely related to the now famous Herbersmithite. Kapellasite shares the same formula as Herbeertsmithite, $Cu_3Zn(OH)_6Cl_2$, but features a more 2-dimensional structure made up of layers held together by hydrogen bonding. This structure is expected to stabilise the low dimensional properties of this quantum magnet to the effects of Cu/Zn site mixing, making it an interesting model magnet. Haydeeite, is the Mg analogue, $Cu_3Mg(OH)_6Cl_2$, and is notable in that it displays magnetic long range order at low temperatures.

The last material, Fe_3Sn_2, shows evidence of being a frustrated ferromagnetic metal that features both localised and itinerant electrons. Previously thought of as a conventional ferromagnet, we show using a combination of SQUID measurements, symmetry analysis and powder neutron diffraction, that Fe_3Sn_2 is a frustrated ferromagnet with a temperature-dependent non-collinear spin structure. The complexity of the magnetic interactions is further evidenced by what appears to be a re-entrant spin glass transition (Tf~80K) at temperatures far below the main ferromagnetic transition (TC= 640K), and an extraordinary example of the Hall effect.

Financial Report

This is a brief financial report on the highly frustrated magnetism meeting held from the 16th – 18th of September 2009, at the STFC Cosenors house, Abingdon, UK. Receipts have been obtained for all costs and can be supplied if required. We have attempted to break down the costs to make it clear how the allocated money was spent. Some delegates had to make a contribution to their own airfares, this amount was minimized for European scientists (unless the claim was unreasonable), however no more than 50% of the travel costs were made to rest of the world contributors.

Accommodation and meals - £8864.40.

This includes a total of 76 nights accommodation **(£4720)** and all the meals (**£3550.4)** for all the delegates including a conference dinner for 42 people. A significant discount (20%) was achieved by holding the meeting at the Cosenors house as this allowed for the STFC staff discount as one of the conference organizers (S. R. Giblin) works at ISIS. The remaining **£594** was for the conference room.

Airport and Station Transfers - £1070.05.

This was the cost to transfer, to and from the airports/train stations all the delegates over three days. A large percentage of Taxis were full to reduce costs.

Other UK Travel – £534.60

This covers car and train costs for 5 UK delegates who claimed for travel.

European Air Travel - £3198.64

This amount covered the air travel (to the airport on the home side) and the associated flight/train costs for 14 delegates.

Rest of World Air Travel - £1936.47

This amount covered the international travel for 5 delegates. All the rest of the world delegates contributed at least 50 % of their own travel.

Organisers Expenses £100

This covers the expenses of S. Bramwell and S. R. Giblin whilst arranging the meetings and covers train fares to and from London and Oxford.
The total paid by the ESF to the organisers so far (80% of the grant) is **£12545**, the remaining 20% (~**£3150**) of the grant should cover the costs of the conference.

To fill in the online form we assumed the exchange rate 0.8918 Euros = 1GBP