Advanced Working Group on Monopoles in Spin Ice
Royal Holloway, University of London
15th and 16th October 2010

Summary

Recent developments in the physics of spin ice have identified low-temperature excitations in the form of emergent magnetic monopoles. These couple to laboratory magnetic fields and exhibit mutual magnetic Coulomb interactions. Since 2008 there have been several high impact publications in this area including 5 in Science or Nature group journals. The field is rapidly advancing, with many new ideas being proposed, and new avenues explored. This is true both on the theoretical and the experimental fronts.

This workshop was designed as a platform to bring together the groups actively working in the field, in order to focus their respective research efforts, exchange information and ideas, and initiate further collaborations. We therefore chose the format of an `Advanced Working Group' to bring together the experts in the field, theorists and experimentalists, to discuss both work in progress and the conclusions of recently published work.

The format was efficient in that even though the total duration of the meeting was shy of two full days, its sharp focus allowed for a high information flux rate. In advance of the workshop, we had contacted a handful of participants asking them to provide an hour-long overview of an aspect of the field. These presentations were supplemented by 10+5 minute presentations on individual research results/work in progress/conceptual questions by the other participants. On top of this, much time was allocated for free and targeted discussions.

Almost all the European groups were represented at the meeting. In addition, there was good attendance from the leading players from abroad, in particular from America (Michel Gingras, Waterloo; Jason Gardner, NIST).

The meeting provided an overview of the current, and projected, research activity in the field, as we discuss in the next section. We have received very positive feedback from the participants. Overall, we feel that the format of our event nicely complemented the broader meetings, such as the ones held in Lalonde or Trieste, in the course of the HFM programme.

Description of the scientific content of and discussion at the event

Day one of the conference began with welcome speeches by Claudio Castelnovo, principal organiser of the meeting, and A. Taylor, Head of the Rutherford Appleton Laboratory and Director of the ISIS neutron and muon facility.

The first session, "static and dynamic fluctuations in spin ice I" began with the review talk by Martin Orendac "Thermodynamic measurements of spin ice", who provided a survey of thermodynamic measurements done on spin ice materials over the last 10-12 years. This covered specific heat measurements showing the existence of Pauling entropy and a review of the response of Dysprosium and Holmium Titanate to magnetic fields along different crystalline axes. The second half of the presentation covered in detail experiments performed by Orendac and collaborators studying magnetocaloric effects through adiabatic demagnetisation of Dysprosium Titanate within the low temperature phase, where the ice rules are largely enforced. From these experiments one is able to extract macroscopic relaxation time scales. One finds a crossover to a regime with long relaxation times below 300mK, an effect that is currently largely unexplained.

Orendac's review was followed, in "static and dynamic fluctuations in spin ice II" by short talks by Alan Tennant, Ludovic Jaubert and Peter Holdsworth. Tennant presented recent experimental developments from the Berlin group at the Helmholtz Zentrum. In particular he presented unpublished data on thermal transport properties of Dysprosium Titanate. They find that thermal conductivity values are surprisingly high for an insulating material at low temperature. He also discussed future experiments to measure surface effects due to monopoles and monopole gradients away from free surfaces. Jaubert made a detailed analysis of his work on diffusive dynamics in dipolar spin ice and in a Coulomb gas model for spin ice following from the dumbbell model. Comparing magnetic relaxation data from experiments form the Schiffer group with the diffusive relaxation of these two models he was able to identify a monopole hopping time scale of around a millisecond. Similar trends appear in Holmium Titanate, but the time scale appears to be different by orders of magnitude. Holdsworth presented unpublished simulation data attempting to measure the charge carried by particles in a Coulomb gas using Onsager's theory of the Wien effect. Two models were studied, a primitive Coulomb lattice gas and the spin ice Coulomb gas with kinetic constraints compatible with the classical Dirac strings connecting magnetic charges. Results shown were in reasonable agreement with the theory, suggesting that it does work for these systems. Discussion of these aspects, chaired by Jason Gardener took the conference through to lunch.

The afternoon session "muSR and the Wien effect I" began by a presentation by Stephen Blundell, "muSR and dynamical time scales", in which he reviewed the muSR technique applied particularly to frustrated magnetism and the observed time scales emanating from experiments on Dysprosium Titanate. Blundell discussed in detail the form of the internal magnetic field coming from small clusters of magnetic moments and showed unpublished calculations of the magnetic field emanating from a tetrahedron of point moments satisfying the ice rules. He concluded that the zones in space corresponding to zero field were exceedingly small. From this he further concluded that it was difficult to envisage a scenario with muons localised inside such a classical array of dipoles and relaxing as if in a small field on the Tesla scale, as seems to be the case in a recent muSR experiment by Bramwell, Giblin and collaborators on a sample of Dysprosium Titanate.

This was followed by Steven Bramwell, whose presentation "The Wien Effect in Spin Ice", reviewed Onsager's theory of the Wien effect, with particular reference to spin ice and to recent experiments on Dysprosium Titanate by himself and collaborators. After introducing the different length scales of the problem (Bjerrum length, Debye length, drift length) the results of both their experiments, interpreting muon relaxation rates in terms of Wien parameters and their magnetic relaxation experiment were discussed. For the former, the question of where the muons are implanted in the sample, which motivated much discussion during the conference, was briefly addressed and phenomenological arguments were presented showing how information on monopole dynamics and static correlations could be gained from muons sitting either inside, or outside the sample. In the latter experiment, magnetic relaxation protocols have been interpreted in terms of monopole currents and Debye relaxation of bound pairs of magnetic charges. The coupled two-time relaxation was presented in analogy with dielectric relaxation of a "leaky capacitor". He showed that results correspond accurately to the Wien phenomenology and proposed that the results give weight to the comparison of the monopole system with an electrolyte, suggesting the terminology of a "magnetolyte" for spin ice at low temperature. The seminar ended with a brief presentation of unpublished dimensional analysis of the behaviour of these length scales in different temperature regimes. It was shown that a semi-quantitative description of the magnetic response of spin ice materials can be achieved from dimensional analysis, including the field cooled/zero field cooled splitting of the susceptibility observed for Dysprosium Titanate below 650 mK.

The session "muSR and the Wien effect II" consisted of two short talks by Yasutomo Uemura and Sean Giblin giving conflicting points of view on Bramwell, Giblin and collaborators recent muSR experiment on Dysprosium Titanate. Uemura presented unpublished data, claiming to show that the muons in the Bramwell/Giblin experiment must be situated outside the sample of Dysprosium Titanate and that the signal recorded comes mostly from background noise rather than from the sample. When questioned on whether an attempt had been made to reproduce the experimental results of Bramwell and Giblin, his reply was that no such attempt had been made. Giblin presented unpublished data from recent muSR experiments showing the difference in signal when the order of the Dysprosium Titanate sample and silver sample support were reversed in the line of flight of the muons. His interpretation of the data was that a spin ice related signal most definitely exists and the experiments cannot exclude the presence of muons within the sample. The ensuing discussion took us to the end of the day.

The second day began with the session "Spin ice out of equilibrium I" and a presentation, "Non-equilibrium phenomena and the freezing transition", by Santiago Grigera. Here, Grigera reviewed recent experiments showing non-equilibrium phenomena on applying a [111] field to Dysprosium Titanate at low temperature. Time dependent jumps in the magnetisation on increasing the field and memory effects reminiscent of glassy systems characterise the rise from zero magnetisation up to the 1/3 plateau at stronger fields. The jumps, whose amplitude varies with the time scale of the applied field, are bounded by an adiabatic magnetisation curve. The jumps can be interpreted in terms of avalanches of overturned spins: propagation of monopoles in the direction of the field leads to localised and preferential heating, which facilitates the further propagation of monopoles along the field direction and an avalanche effect in some sense analogous to dielectric breakdown. The theory corresponds to unpublished work in collaboration with Claudio Castelnovo and Roderich Moessner. The session "Spin ice out of equilibrium II" followed with a short presentation by Steven Bramwell, "Dimensional Analysis and Spin Freezing in Spin Ice", in which the unpublished

phenomenological approach begun on day one was completed with more details and discussions.

The second session of the day, "New Compounds" took us away from Dysprosium Titanate, beginning with a presentation by Michel Gingras on "The problem of long range order in Tb2Sn2O7 and spin liquid in Tb2Ti2O7". Here, Gingras reviewed the physics of these two materials, in which quantum fluctuations play a fundamental role and both of which present longstanding unsolved problems. He first reviewed how, on changing the degree of energy scale separation in models for spin ice materials, quantum fluctuations can begin to play a role. Critically, in these materials the energy scale to the first excited crystal field state is in the 10-20 K range, an order of magnitude smaller than for Holmium and Dysprosium Titanate. The second key factor in describing these materials is the inclusion of dipole interactions, which typically are the same order of magnitude as exchange. The presentation then continued with unpublished calculations showing how an effective Hamiltonian taking into account this physics predicts, for Tb2Sn2O7, ordering to a ferromagnetically ordered state with an unusual canting of magnetic moments away from classical spin ice directions. This canting, which reduces the moment compared with an ordered state from the classical spin ice state, is exactly that observed in experiment for this material. On the other hand Tb2Ti2O7, which fails to order down to the lowest temperature, remains an enigma even within this new framework, although it does allow for a better understanding of the correlations one can expect given a spin liquid state. This long presentation was followed by three short ones by Jason Gardener, Peter Baker and Tom Fennell. In the first, Gardener exposed the similarities and differences between Pr2M2O7 compounds and conventional spin ice materials (Dy2Ti2O7 and Ho2Ti2O7). In the second, Baker presented preliminary data from a muSR experiment in collaboration with Sean Giblin on the partial magnetisation plateaux emerging from a quantum spin ice state in Tb2Ti2O7 in a [111] field, showing evidence of the reminiscence of spin ice like plateaux, as speculated by Michel Gingras and collaborators. In the third, Fennell provided an analysis of the pinch points found increasingly ubiquitously in the pyrochlores and related systems. Issues discussed included the use of polarised neutrons to bring the pinchpoints into evidence; and the origin of the relatively sharpness of the pinch points even at high temperature.

The final session, "New Compounds II" comprised four short talks by Isabelle Mirebeau, Shegeki Onoda, Nic Shannon and Ludovic Jaubert. Shigeki Onoda talked about mean-field and numerical studies of quantum effects in spin ice. Onoda considered quantum spin ice with a realistic level scheme, starting from which he derived an effective Hamiltonian, the solution of which he proceeded to show for a 16-site cluster. In addition, for the itinerant case of Pr2Ir2O7, he showed how a spin ice arrangements permits to have time-reversal symmetry breaking in the absence of a net magnetic moment. Isabelle Mirebeau talked about field induced magnetic structures in Tb2Ti2O7. She discussed the effects of anisotropic exchange tensors which might arise as a combination of competing super-exchange paths, dipolar interactions and lattice distortions. In this context, the role of small misalignments of applied magnetic fields was discussed. Nic Shannon presented quantum Monte Carlo simulation results for a model of spin ice with quantum fluctuations in the form of loop resonances around closed hexagons on the pyrochlore lattice. He showed that the disordered phase survives quantum fluctuations in the form of a quantum spin liquid with a continuum of excitations out of the singlet ground state. These may be interpreted as `photon' excitations taking the system from one resonance of spin ice states to another with a slightly higher energy. Shannon discussed how, in the future, one could incorporate monopole like excitations into the model. In the final talk, Ludovic Jaubert presented unpublished data from a microscopic analysis of the diffusive dynamics of the dipolar spin ice model and the spin ice

Coulomb gas. By making a `slave' Coulomb gas follow the evolution of the spin model, he was able to show how the energy of creation of a nearest neighbour pair of charged particles evolves with temperature. The evolution illustrates the role played by Debye screening and particle-particle correlations as one moves from a high temperature dense gas of monopoles to a low temperature unscreened gas of particles. Despite strong variations and fluctuations in both the creation energy and the change in Coulomb energy, the chemical potential for pair creation extracted from the spin model remains essentially independent of temperature. Jaubert also briefly discussed the evolution of monopole concentration as the chemical potential is varied away from the values for Dysprosium and Holmium Titanate. He showed evidence of a phase transition in the density for values of the chemical potential near the phase boundary for spin ice physics proposed by Gingras and collaborators for the dipolar spin ice model. It remains to be seen if the transition corresponds indeed to crossing this boundary.

The meeting ended with a discussion session chaired by Steven Bramwell and with the participation, via Skype, of Shivaji Sondhi. Alan Tennant discussed ideas for future Stanford-like experiments for single monopole detection and how single monopoles could be trapped and manipulated. Peter Holdsworth raised the question of whether the present research into spin ice and monopole physics could teach us anything about related problems, for example conductivity in water ice.

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

One of the achievements of this workshop was to highlight through active discussions what is the state of the art regarding magnetic monopole physics in spin ice, reviewing what is by now understood and established and identifying the main open questions that are left to be addressed. For instance, the review by Orendac of magnetocaloric measurements done in 2005-2007 (see summary) evidenced how several open questions about relaxation time scales in spin ice, raised back then and not yet answered, are indeed very topical nowadays in connection to recent thermal transport (see A.Tennant's talk) and magnetisation (see S.Grigera's talk) measurements.

The small size and focused nature of the workshop allowed for a frank information exchange on current activities. In particular, people discussed unpublished work (e.g. thermal conductivity measurements, A.Tennant; dimensional analysis of susceptibility, S.Bramwell; real-time magnetisation processes, S.Grigera; work on effective Hamiltonians, P.Holdsworth; polarised neutron scattering results, T.Fennell), thereby speeding up dissemination of information and precluding duplication. Lively question and answer sessions allowed for immediate feedback from the audience, which the speakers can then incorporate more efficiently at an early stage.

The structure of the workshop allowed also for civilised but thorough discussion of contentious issues. For instance, how can we fully understand muSR measurements in spin ice samples (see for instance the interventions by S.Giblin and Y.Uemura)? Where do the muons sit? The absence of a 1/3 plateau in the muSR asymmetry and the observation of a precessing signal whose period is determined by an external field of 1mTesla indicate that the muons sit at very small field locations (<< 1 mTesla). Moreover, a decaying envelope of the oscillations indicates that these small local fields fluctuate on time scales smaller than 1 microsecond. Both findings are at odds with current knowledge about spin ice $Dy_2Ti_2O_7$, whose internal fields are a sizeable fraction of a Tesla and appear to be static over time scales of the order of 1 ms. Similar discussions arose about the relevant equilibration time scales at different temperatures in spin ice and the agents responsible for them (spins, monopoles, phonons?). Also, regarding neutron scattering measurements, why are the bow-ties sharp at high temperature (see T.Fennell's talk)?

During the workshop, the most promising and interesting future directions were identified, planting the seeds for fruitful collaborations. Amongst others: introducing quantum mechanical effects in spin-ice like compounds (see M.Gingras overview talk) will lead to interesting new behaviours in frustrated magnetic systems and perhaps we will be able to find a quantum mechanical counterpart to magnetic monopole excitations in spin ice. Understanding the effects of point-like Coulomb-interacting excitations when the system is driven strongly out of equilibrium also emerged as one of the leading challenges in spin ice, relating directly to the many past and upcoming out-of-equilibrium measurements on these materials. A separate but closely related issue that was identified is investigating the role of phonon coupling in thermal transport, in an effort to explain why both magnetic and thermal time scales appear to become exceedingly large in these systems below about 600 mK.

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Programme

General Concepts: The purpose of the meeting is to bring together researchers already informed, or active in the field of monopoles in spin ice. While the programme will include short reviews on specific aspects and experimental techniques, it will be assumed that the participants are acquainted with the physics of monopole quasi-particles in spin ice materials from both a theoretical and experimental point of view. The programme will be comprised of focused 1-2 hour colloquia on specific topics, together with chaired discussion periods during which previous themes will be revisited. Each colloquium will begin with one or two review presentations, of maximum length 30 minutes, introducing the specific topic and related open questions. This introduction will be followed by discussion, which can be motivated by short presentations of 5 minutes and two transparencies. Calls will be made to participants wishing to make short presentations.

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Royal Holloway
University of London

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Organisers

Steve Bramwell
Claudio Castelnovo
Peter Holdsworth
Roderich Moessner

Participants

Peter Baker
Steve Blundell
Tom Fennell
Jason Gardner
Sean Giblin
Michel Gingras
Santiago Grigera
Jon Goff
Ludovic Jaubert
Bastian Klemke
Isabelle Mirebeau
Jonathan Morris
Shigeki Onoda
Martin Orendac
Oleg Petrenko
Dharmalingam Prabhakaran
Jorge Quintanilla
Nic Shannon
Andrew Taylor
Alan Tennant
Yasutomo Uemura (remote link)

Friday 15th of October:

[Welcome DINNER at Founders Building 19.00 – 21.00 on Thursday, Oct.14]

Breakfast at The Hub: 7:30-8:45
Walk from The Hub to RHUL Founders Building: 6 mins
Free Shuttle from RHUL Founders Building to Kingswood Blue room: leaving at 8:35, 8:55, arriving at 8:44, 9:04

[C0] 9.10 – 9.30 Opening
C. Castelnovo: welcome!
A.Taylor (ISIS): SEPnet and the ISIS-RHUL-UCL Hubbard Theory Centre

[C1] 9.30 – 10.20 Static and dynamic fluctuations in spin ice I
M. Orendac, "*Thermodynamic measurements of spin ice*" (40+10 mins)

COFFEE 10.20 – 10.45

[C2] 10.45 – 11.30 Static and dynamic fluctuations in spin ice II
A. Tennant, "*Recent scattering and thermodynamic measurements at HZB*" (10+5 mins)
L. Jaubert, "*Monopole dynamics in spin ice*" (10+5 mins)
P. C.W. Holdsworth, "*Some simulation results for the Wien effect*" (10+5 mins)

[S1] 11.30 – 12.30 Discussion – chair J. Gardner

LUNCH at Kingswood 12.30 – 13.30

[C3] 13.30 – 15.30 muSR and the Wien effect I
S. Blundell, "*muSR and dynamical time scales*" (50+10 mins)
S. Bramwell, "*The Wien Effect in Spin Ice*" (50+10 mins)

TEA 15.30 – 16.00

[C4] 16.00 – 16.30 muSR and the Wien effect II
T. Uemura (cyberconf), "*Did MuSR detect magnetic monopoles in Dy2Ti2O7?*" (10+5 mins)
S. Giblin, "*muSR and spin ice*" (10+5 mins)

[S2] 16.30 – 18.30 Discussion – chair R. Moessner

Free Shuttle from Kingswood to RHUL Founders Building: leaving at 18:25, 18:45, 19:05, arriving at 18:34, 18:54, 19:14.

Buffet DINNER at Founders Building 19.00 – 21.00

Walk back from Founders Building to lodgings (The Hub): 6 mins.

Saturday 16th of October

Breakfast at The Hub: 7:30-8:15
Walk from accommodation (The Hub) to Kingswood Blue room: leaving at 8:20, arriving at 8:50-8:55. [A shuttle service will be provided in case of adverse weather.]

[C5] 9.00 – 10.00 Spin ice out of equilibrium I
S. Grigera, "*Non-equilibrium phenomena and the freezing transition*" (50+10 mins)

[C6] 10.00 – 10.15 Spin ice out of equilibrium II
S.T. Bramwell "*Dimensional Analysis and Spin Freezing in Spin Ice*" (10+5 mins)

COFFEE 10.15 – 10.45

[S3] 10.45 – 11.30 Discussion – chair M. Gingras

[C7] 11.30 – 13.15 New compounds I
M. J. P. Gingras "*The problem of long range order in Tb2Sn2O7 and spin liquid in Tb2Ti2O7*" (50+10 mins)
J. Gardener "*Pr2M2O7*" (10+5 mins)
P. Baker "*Partial magnetization plateau emerging from a quantum spin ice state in Tb2Ti2O7*" (10+5 mins)
T. Fennell "*Pinch-points in spin ice and related materials*" (10+5 mins)

LUNCH at Kingswood 13.15 – 14.00

[C8] 14.00 – 15.00 New compounds II
I. Mirebeau, "*Field induced magnetic structures in Tb2Ti2O7*" (10+5 mins)
S. Onoda, "*Mean-field and numerical studies on quantum effects in spin ice*" (10+5 mins)
N. Shannon, "*Quantum Spin Ice*" (10+5 mins)
L. Jaubert, "*Monopoles away from spin ice: chemical potential variation*" (10+5 mins)

TEA 15:00 – 15:30

[S4] 15.30 – 16.30 Closing discussion: "*The future of spin ice*" – chair S. Bramwell

Free Shuttle Bus from Kingswood to Founders Building: departing at 15:00, 16:00, 17:00, 18:00 (travel time: 9 mins).