Third annual workshop of the Helmholtz Virtual Institute

“New states of matter and their excitations”

Berlin, June 16-19, 2015

Program and abstract booklet

Venue: BESSY II on the Wilhelm-Conrad-Röntgen Campus of HZB, Berlin-Adlershof, Albert-Einstein-Straße 15, 12489 Berlin

Organizers: Johannes Reuther & Ralf Feyerherm
Local support: Sophie Spangenberger, Juliane Hantschke and others
How to get there:

**Location for Dinner: Ratskeller Köpenick**, Alt-Köpenick 21, 12555 Berlin
Easy to reach or leave by tram 60/61

On Wednesday evening there will be a bus shuttle starting 18:30 h in front of Hotel Dorint and returning to the hotels at 22:00 h
Scientific program of the Helmholtz Virtual Institute Workshop
“New states of matter and their excitations”
June 16, 2015 - June 19, 2015, Berlin-Adlershof

Tuesday, June 16

8:45  Registration (BESSY)
9:45 - 10:00  Opening

Tutorial I
Chair: Johannes Knolle

10:00 - 11:15  Matthias Vojta (TU Dresden)
Kitaev spin liquids

11:15 - 11:30 Coffee break

11:30 - 12:45  Ronny Thomale (University of Würzburg)
Entanglement spectra and topology in strongly correlated electron systems

12:45 - 14:00 Lunch buffet at BESSY foyer

Chair: Johannes Reuther

14:00 - 15:15  Santiago Grigera (University of La Plata)
Experimental low temperature techniques in magnetic and electronic systems

15:15 - 15:30 Coffee break

15:30 - 16:45  Felix von Oppen (FU Berlin)
Magnetic adatoms on superconductors - a new venue for Majorana bound states?

Wednesday, June 17

Workshop
Chair: John Chalker

9:30 - 10:05  Claudio Castelnovo (University of Cambridge)
Critical dynamics and finite-time scaling in spin ice systems

10:05 - 10:40 Olga Petrova (MPI PkS Dresden)
Magnetic monopoles in diluted quantum spin ice
10:40 – 11:20 Coffee break

11:20 - 11:55 **Philipp Gegenwart** (University of Augsburg)
*Kitaev exchange interaction in spin-orbit Mott insulators*

11:55 - 12:30 **Simon Trebst** (University of Köln)
*Majorana metals and quantum spin liquids*

12:30 - 13:30 Lunch buffet at BESSY foyer

13:30 - 15:35 Discussions & BESSY tours (groups A &B)

*Chair: Oliver Rader*

15:35 - 16:10 **Stephan Rachel** (TU Dresden):
*Quantum disordered insulating phase in the frustrated Hubbard model on the cubic lattice*

16:10 - 16:30 Coffee break

16:30 - 17:05 **Laurens W. Molenkamp** (U Würzburg)
*HgTe as a topological insulator*

17:05 - 17:40 **Katja Nowack** (Cornell University)
*Imaging current in quantum spin Hall insulators*

19:00 - 22:00 Workshop Dinner at “Ratskeller Köpenick”

**Thursday, June 18**

**Workshop**
*Chair: Andreas Honecker*

9:30 - 10:05 **Piet Brouwer** (FU Berlin)
*Disorder-induced phase transition in Dirac semimetals*

10:05 - 10:40 **Christian Pfleiderer** (TU München)
*Topological unwinding of skyrmions in chiral magnets*

10:40 - 11:20 Coffee break & poster mounting

11:20 - 11:55 **Kai P. Schmidt** (TU Dortmund)
*Tackling complex quantum magnets with linked cluster expansions*

11:55 - 12:30 **Ekaterina Klyushina** (Helmholtz-Zentrum-Berlin)
*Asymmetric Thermal Lineshape Broadening in the Dimerised Antiferromagnet BaCu$_2$V$_2$O$_8$*
12:30 - 13:20  Lunch buffet at BESSY foyer

13:30 - 15:35  Discussions & BESSY tours (groups C, D, E)

   Chair: Dominik Ixert

15:35 - 16:10  Stefanie Thiem (U Oxford)
   Magnetism in Rare Earth Quasicrystals: RKKY Interactions and Ordering

16:10 - 16:30  Coffee break

16:30 - 17:05  Veronika Fritsch (U Augsburg)
   Metallic Spin Liquids in f-electron systems

17:05 - 17:40  Emile Rienks (HZB)
   Samarium hexaboride: Exciting states of old matter

18:00 - 21:00  Poster session (including buffet and beverages)

Friday, June 19

   Tutorial II
   Chair: Björn Sbierski

9:00 - 10:15  Salvatore Manmana (U Göttingen)
   Numerical Matrix Product States Methods

10:15 - 10:30  Coffee break

10:30 - 11:45  Götz Uhrig (U Dortmund)
   Effective Models from Continuous Unitary Transformations

11:45 - 13:00  Lunch buffet at BESSY foyer

   Chair: Alexander Tiegel

13:00 - 14:15  Markus Morgenstern (RTWH Aachen)
   Topological properties in solids probed by experiment

14:15 - 14:30  Coffee break

14:30 - 15:45  Emil Bergholtz (FU Berlin)
   Chern insulators and their relatives

15:45  End of workshop / Departure
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Abstracts

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Tutorial: Kitaev spin liquids

Matthias Vojta
TU Dresden

After a general introduction to spin-liquid phases, I will discuss the particular case of Kitaev's compass model of the honeycomb lattice which constitutes a rare case of an exactly solvable model for a spin liquid in two spatial dimensions. Its emergent degrees of freedom are fermion excitations, either gapless or gapped, and static $\mathbb{Z}_2$ gauge fluxes. I will present the formal solution in terms of Majorana fermions as well as results for various observables, including the finite-temperature and finite-field cases. Generalizations to other lattices and the effects of additional interactions and disorder will be discussed as well.
Entanglement spectra and Topology in strongly correlated electron systems

Ronny Thomale
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Since its development for non-interacting [1] and interacting [2] systems, entanglement spectra (ES) have become one of the most versatile tools to analyze topological quantum states of matter. In this talk, we review the notion of an entanglement gap separating low-energy, topological levels, from high-energy, generic ones, in the ES of fractional quantum Hall (FQH) states and quantum spin chains. We illustrate how the ES of an incompressible ground state of a generic (i.e. Coulomb) lowest Landau level Hamiltonian rearranges into a low-(entanglement) energy part separated by a full gap from the ”high energy” entanglement levels [3]. The counting of these levels starts off as the counting of modes of the edge theory of the FQH state, but quickly develops finite-size effects which we show can also serve as a fingerprint of the FQH state. By using the adiabatic continuity of the low entanglement energy levels, we investigate whether two states are topologically connected.

For spin chains, it becomes transparent how to exploit the feature that ES are a basis-dependent quantity. The ES from a cut in momentum space allows to study the dimerization transition, bulk excitation state counting, and the manifestation of logarithmic CFT corrections purely from the ground state wave function [4, 5]. The ES from a cut in real space allows to resolve symmetry breaking and topology already for small system sizes, which we illustrate for the bilinear-biquadratic Heisenberg spin chain [6].

References

Experimental low temperature techniques in magnetic and electronic systems

Santiago Grigera (La Plata & St. Andrews)

In this talk we will do a tutorial review on several classical experimental techniques used at low temperatures to study magnetic and electronic systems. Among them, specific heat, magnetocaloric effect, quantum oscillations (dHvA, SdH, etc.), magnetisation, susceptibility, and show some examples of applications to different systems.
Magnetic adatoms on superconductors - a new venue for Majorana bound states?

Felix von Oppen (FU Berlin)

In this talk, I discuss a possible new platform for realizing Majorana modes in condensed matter systems, namely chains of magnetic adatoms on conventional superconductors. In a recent experiment, Nadj-Perge et al. (Science 2014) provided possible evidence for Majorana bound states based on this platform, using Fe impurities on a Pb substrate. The formation of topological superconductivity in this system relies on ferromagnetic order of the magnetic moments and spin-orbit coupling of the substrate superconductor. Specifically, I will review a physical picture underlying these experiments which starts with the physics of individual magnetic adatoms, including a possible explanation for the unexpectedly strong localization of the observed end states.
Spin ice materials such as Dy2Ti2O7 and Ho2Ti2O7 provide a rare instance of emergent gauge symmetry and fractionalisation in three dimensions. Magnetic frustration leads to highly degenerate yet locally constrained ground states. Their elementary excitations carry a fraction of the magnetic moment of the microscopic spin degrees of freedom and can be thought of as magnetic monopoles. One of the distinguishing manifestations of this emergent “Coulomb phase” is a liquid-gas phase diagram that appears in an applied magnetic field – a feature that is expected in itinerant charge liquids but unprecedented in localised spin systems. Monopoles act as facilitators to the spin dynamics. At low temperatures they are sparse and dynamics becomes slow, leading to an interplay between emergent topological properties and lattice scale physics in response and equilibration properties. In this work, we investigate the dynamics in spin ice close to the critical end point of the liquid gas phase diagram. Critically divergent length scales give rise to finite time scaling properties that reflect the universal scaling exponents at the critical point. We use our results to obtain these exponents by tuning the approach direction in the field-temperature plane.
Magnetic monopoles in diluted quantum spin ice

Olga Petrova,1 Roderich Moessner,1 and S. L. Sondhi1,2

1Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany
2Department of Physics, Princeton University, Princeton, NJ 08544, USA

Quantum spin ice is a topic of much current interest, stemming from its promise as a topological spin liquid in 3d, as well as recent discoveries of candidate compounds. However, precisely what signatures to look for to nail down quantum behavior in spin ices is not clear. In this talk I will show that the most visible place to look for quantum effects in spin ice is in the presence of emergent magnetic monopoles, whose fractionalized nature is perhaps the most striking feature of this system.

Our focus is on the case of weakly diluted quantum spin ice, where we find the emergence of hydrogenic excited states, resembling those in doped semiconductors, in which a magnetic monopole is bound to the vacancy at various distances. We obtain an approximate expression for the neutron scattering dynamic structure factor [1] via a mapping to an effective exactly solvable model defined on the Bethe lattice.

References:
Kitaev exchange interaction in spin-orbit Mott insulators

*Philipp Gegenwart*

Experimentalphysik VI, Center for Electronic Correlations and Magnetism, Augsburg University, Germany

Hexagonal iridates $A_2$IrO$_3$ ($A$=Na, Li) are discussed in the context of realizing magnetic Kitaev exchange between $j=1/2$ moments. This talk reports experimental investigation of magnetic properties of Na$_2$IrO$_3$ and α-Li$_2$IrO$_3$, crystallizing in a layered honeycomb structure, as well as, the related “hyper-honeycomb” β-Li$_2$IrO$_3$. For the latter material, very recent magnetic resonant X-ray diffraction experiments allowed a complete solution of the magnetic structure. Incommensurate magnetic order with non-coplanar and counter-rotating Ir moments are found, similar as also realized in another polytype, the “stripyhoneycomb” γ-Li$_2$IrO$_3$. Theoretically, such structure is stabilized by dominant Kitaev interactions. The similarities between the two materials which share similar local connectivity between the Ir neighbors suggest dominating Kitaev magnetic exchange in both materials.

Work in collaboration with F. Freund, S. Manni, A. Jesche, Y. Singh, S. Choi and R. Coldea.
Majorana metals and quantum spin liquids

S. Trebst (University of Cologne)

One of the most intriguing phenomena in strongly correlated systems is the fractionalization of quantum numbers — familiar examples include the spin-charge separation in one-dimensional metallic systems, the fractionalization of the electron in certain quantum Hall states or the emergence of monopoles in spin ice.

In this talk, I will discuss the fractionalization of magnetic moments in a certain class of Mott insulators, in which the emergent degrees of freedom are Majorana fermions that form an (almost) conventional metal. The origin of such a dichotomous state is elucidated by a family of exactly solvable (Kitaev-type) models of frustrated quantum magnets in three dimensions, which might be realized in a class of recently synthesized Iridate compounds. These models thereby provide the first analytical tractable examples of long sought-after quantum spin liquids with a spinon Fermi surface [1] and even an entirely new class of quantum spin liquids — a Weyl spin liquid, in which the fractionalized degrees of freedom form a topological semi-metal [2].

Work done in collaboration with Maria Hermanns and Kevin O’Brien.

Exotic phases in extended Kitaev models

Stephan Rachel

1Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden

Abstract

Heisenberg-Kitaev models have been successfully used to describe the exotic magnetic phases as well as the predicted spin-liquid phases of certain honeycomb-lattice transition metal oxides (TMO). While the original proposal of Jackeli and Khaliullin contained a nearest-neighbor Heisenberg spin exchange as well as the exactly solvable nearest-neighbor Kitaev-term, recently it has been pointed out that second-neighbor Kitaev exchange plays a significant role. Here we propose the $K_1-K_2$ model featuring the following properties:

1. it describes the magnetic phases of all the debated honeycomb TMOs and serves as a minimal model,

2. it contains not only the Kitaev spin liquids but also a plethora of exotic magnetic phases,

3. its zero-temperature quantum phase diagram is fully distinct from its classical finite-temperature counterpart.
HgTe as a Topological Insulator

L.W. Molenkamp

Physics Institute (EP3), Wuerzburg University, Am Hubland, Wuerzburg 97074, Germany

HgTe is a zincblende-type semiconductor with an inverted band structure. While the bulk material is a semimetal, lowering the crystalline symmetry opens up a gap, turning the compound into a topological insulator. The most straightforward way to do so is by growing a quantum well with (Hg,Cd)Te barriers. Such structures exhibit the quantum spin Hall effect, where a pair of spin polarized helical edge channels develops when the bulk of the material is insulating. Our transport data[1-3] provide very direct evidence for the existence of this third quantum Hall effect, which now is seen as the prime manifestation of a 2-dimensional topological insulator.

To turn the material into a 3-dimensional topological insulator, we utilize growth induced strain in relatively thick (ca. 100 nm) HgTe epitaxial layers. The high electronic quality of such layers allows a direct observation of the quantum Hall effect of the 2-dimensional topological surface states[4,5]. Due to the screening properties of Dirac fermions, these states turn out to be decoupled from the bulk for a very wide range of densities[5]. This allows us to induce a supercurrent in the surface states by contacting these structures with Nb electrodes[6]. AC investigations indicate that the induced superconductivity is strongly influenced by the helical character of the charge carriers.

Conducting edge modes at the sample boundaries are a key feature of the quantum spin Hall (QSH) state, which was predicted and experimentally demonstrated first in HgTe quantum wells and more recently in InAs/GaSb quantum wells. The existence of the edge modes has been evidenced by conductance measurements on sufficiently small devices. In this talk I will describe how we use scanning superconducting interference device (SQUID) microscopy to directly observe and characterize edge current in both materials. From images obtained with the SQUID we reconstruct 2D current densities with a spatial resolution of several microns. In HgTe and InAs/GaSb we show that the edges of the devices carry most of the current when the devices are tuned into their insulating gaps, directly confirming the presence of the edge modes. In addition, we disentangle conduction through the edges and the interior of a device, allowing us to study the resistance of only the edges even when the interior becomes conductive through either gating or raising the temperature. Our analysis suggests that the edge resistance is constant over a large temperature range which we will discuss in the context of proposed scattering mechanisms between the edge modes.
Disorder-induced phase transition in Dirac semimetals

Piet Brouwer (FU Berlin)

Three-dimensional Dirac and Weyl semimetals exhibit a disorder-induced quantum phase transition between a semimetallic phase at weak disorder and a diffusive-metallic phase at strong disorder.

Despite considerable effort, both numerically and analytically, the critical exponents and $z$ of this phase transition are not known precisely. We have numerically investigated the effect of this transition on transport properties, such as the conductance and the shot noise power, and calculated the critical exponents using a minimal single-Weyl cone model and a finite-size scaling analysis of conductance.
Topological unwinding of skyrmions in chiral magnets

C. Pfleiderer
1Physik-Department, Technische Universität München, D-85748 Garching, Germany

The emergence, stability and decay of skyrmions in chiral magnets and the associated emergent electrodynamics are reviewed. The non-zero topological winding, which corresponds to precisely one quantum of emergent magnetic flux, mediates an extremely efficient coupling between the conduction electrons and the magnetic properties. This emergent flux leads to a topological Hall signal, spin transfer torques at ultra-low current densities and emergent electric fields. Additionally skyrmions are characterised by an exceptional stability, which cannot be simply suppressed under large hydrostatic pressures or doping. The topological unwinding of skyrmions as inferred from a combination of magnetic force microscopy, small angle neutron scattering and Monte-Carlo simulations suggests distinct differences of the decay mechanism depending on the final state. In contrast, the underlying energetics appears to be rather similar, characteristic of a rather band width instead of unique energy scales.
Tackling complex quantum magnets with linked cluster expansions

We discuss recent developments to describe elementary excitations in complex quantum magnets using linked cluster expansions. To this end a novel white graph expansion is introduced especially well suited for systems with several coupling constants and/or in higher dimensions. Our scheme is exemplified for a two-dimensional quantum spin model of coupled two-leg XXZ ladders relevant for the quantum antiferromagnet C9H18N2CuBr4 as well as for the highly frustrated transverse-field Ising model on the three-dimensional swedenborgite lattice.
Asymmetric Thermal Lineshape Broadening in the Dimerised Antiferromagnet \( \text{BaCu}_2\text{V}_2\text{O}_8 \)

In the conventional picture, magnetic excitations are long-lived at low temperatures with decreasing lifetime as temperature is increased. The accepted explanation is that thermally activated excitations collide with each other limiting their lifetimes - an effect observed experimentally as a Lorentzian energy broadening of the lineshape. This picture works well for gapless magnets with long-range magnetic order \([1,2]\). The basic assumption is that the excitations interact only weakly and the available states cover a big region of phase space, so that as they collide they fluctuate randomly among a large range of different states in an uncorrelated manner. However for some magnets, where there are strong interactions between the excitations and the phase space is limited, this reasoning may not apply \([3,4]\). Gapped antiferromagnets such as dimer systems which have a singlet ground state and a band of triplet excitations are potential candidates.

In this present work we introduce our recent investigations of a highly dimerised 1D antiferromagnet \( \text{BaCu}_2\text{V}_2\text{O}_8 \) which is a potential candidate for the observation of asymmetric thermal line shape broadening. \( \text{BaCu}_2\text{V}_2\text{O}_8 \) has tetragonal symmetry (I-42d, \( a=b=12.66843 \, \text{Å}, c=8.124 \, \text{Å} \)) where the magnetic \( \text{Cu}^{2+} \) ions (spin-1/2) form alternating spiral chains along the c-axis. Our inelastic neutron scattering measurements of \( \text{BaCu}_2\text{V}_2\text{O}_8 \) reveal that the one-magnon excitation spectrum consists of two excitation branches which have a gap of 36meV and disperse along the L direction over the energy range 36-46 meV. Both modes are dispersionless along the H and K directions which imply that the dimers are coupled together one-dimensionally along the c-direction, but with negligible coupling within the a-b plane. Both modes are identical except that they are shifted with respect to each other by half a period along L. DMRG simulations of the magnetic excitation spectra using a model where the \( \text{Cu}^{2+} \) magnetic ions form spiral alternating chains along the c axis and interact via \( \text{Cu-O-Cu} \) and \( \text{Cu-O-V-O-Cu} \) exchange paths provide good agreement with the experimental data at base temperature. The high ratio of gap to bandwidth (=3.6) in \( \text{BaCu}_2\text{V}_2\text{O}_8 \) make this a candidate compound for detailed observation for asymmetric thermal lineshape broadening over a wide temperature range.

In order to explore the temperature dependence of the line shape of the magnetic excitations we perform energy scans at the dispersion minima at different temperatures. The data were fitted well by an asymmetric Lorentzian function and the extracted fit parameters suggest that the line shape becomes increasingly asymmetry with increasing temperature. The results are in agreement with the recently explored temperature dependence of the magnetic excitation spectrum of copper nitrate, which is a spin-1/2 alternating chain with a similar ratio of gap to band width (=3.5) \([4]\). As for copper nitrate, the asymmetry thermal line shape broadening in \( \text{BaCu}_2\text{V}_2\text{O}_8 \) can be attributed to strong correlations between the excitations. This result confirms that excitations in strongly dimerised 1D magnetic systems behave as a 1D strongly correlated gas of Bosons \([4]\).

References:
Magnetism in Rare Earth Quasicrystals: RKKY Interactions and Ordering

Stefanie Thiem and J. T. Chalker

Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom

We study magnetism in simple models for rare earth quasicrystals, by considering Ising spins on a quasiperiodic tiling, coupled via RKKY interactions [1]. Computing these interactions from a tight-binding model on the tiling, we find that they are frustrated and strongly dependent on the local environment. Although such features are often associated with spin glass behaviour, we show using Monte Carlo simulations that the spin system has a phase transition to a low-temperature state with long-range quasiperiodic magnetic order.

In a spin liquid thermal or quantum fluctuations prevent spin ordering or freezing despite the presence of a sufficient magnetic exchange interaction. Such fluctuations can be induced by magnetic frustration preventing magnetic order. In metallic systems Kondo screening can reduce the size of the local magnetic moments due to their hybridization with the conduction electrons and thus suppress the magnetic order as well. It was recently discussed theoretically that strong quantum fluctuations lead to a breakdown of Kondo screening. The result is a state with the conduction electrons separated from the local moments, which are not magnetically ordered and form a spin liquid [1]. Possible experimental realizations of this scenario are found in Pr$_2$Ir$_2$O$_7$ [2] and CeRhSn [3] as well as CePdAl [4]. In the latter material neutron scattering experiments and measurements of magnetization, specific heat and electrical resistivity have provided evidence for the emergence of a partial spin liquid state established by $1/3$ of the Ce moments.

Work in collaboration with W. Kittler, C. Taubenheim, K. Grube and H. v. Löhneysen (Karlsruher Institut für Technologie); Z. Hüsges, S. Lucas, C.-L. Huang and O. Stockert (Max-Planck Institut für chemische Physik fester Stoffe, Dresden); E. Green (Helmholtz-Zentrum Dresden-Rossendorf); A. Sakai, and P. Gegenwart (Universität Augsburg).

Since topological insulators have been established as a new state of matter, a lot of work is devoted to the question whether this concept can be generalized to materials with more prominent electron correlation. As a result, Kondo insulators, a family of strongly correlated materials, have been proposed to be topologically nontrivial [1]. This suggestion revived interest in SmB₆, the prime candidate for such a topological Kondo insulator. Could this material after being identified as the first mixed valence system in the 1960s and the first Kondo insulator shortly after, now become synonymous with yet another phenomenon in solid state research?

The numerous experimental reports that have appeared over the past two years have failed to answer this question convincingly. In this contribution we present results from high-resolution angle-resolved photoemission experiments [2]. We show that the surface properties of SmB₆ are unusual but can be understood entirely in a topologically trivial manner: While surface states are indeed found at the sites where Dirac cones are predicted, we present strong evidence that these are of trivial nature. Our results on the bulk band structure further point at a trivial insulating phase.

Numerical Matrix Product States Methods

Salvatore R. Manmana
Institut für Theoretische Physik
Georg-August-Universität Göttingen, Germany

April 24, 2015

In this tutorial I will give an overview on modern numerical techniques based on so-called Matrix Product States (MPS). I will start reviewing the original approaches relying on the density-matrix-renormalization group (DMRG) which was introduced in 1992 by S.R. White and which has become one of the most successful techniques for the treatment of low-dimensional quantum many body systems. Later, it became apparent from a quantum information perspective how to see this technique in the broader context of MPS, leading to a variety of interesting developments. From these, I will focus on methods for the nonequilibrium time evolution and on approaches to dynamical structure factors at finite temperatures which work very reliably at least in (quasi-)1D structures. I will conclude with an outlook to future perspectives of the methods.
Effective Models from Continuous Unitary Transformations

Abstract:

Diagonalization or simplification of quantum mechanical Hamiltonians by unitary transformations is a standard approach in theoretical physics. We discuss the advantages to perform such a transformation continuously. For practical applications we discuss various realizations such as perturbative and self-similar CUTs and extensions of them such as (de)epCUT or gCUT. Current challenges comprise unstable quasi-particles, anyonic excitations, higher dimensional systems and gapless systems.
Topological properties in solids probed by experiment
M. Morgenstern
II. Institute of Physics and JARA-FIT, RWTH Aachen, D-52074 Aachen, Germany
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Topology is a new paradigm in solid state physics predicting robust physical properties by so-called topological indices arising from a fundamental analysis of the Hamiltonian. Within this talk, I will concentrate on the experimental evidence for these properties mainly in electrical transport, angular resolved photoelectron spectroscopy, and scanning tunneling microscopy. This will start with the seminal experiment on the 2D topological insulator HgTe and will cover weak and strong 3D topological insulators, the quantum anomalous Hall effect and topological crystalline insulators. Moreover, the topological pioneer of solid state systems being the quantum Hall effect will be discussed in terms of topology.

Left: Local density of states responsible for quantum Hall transitions as measured by scanning tunneling microscopy; right: STM image of a zigzag step edge of the weak topological insulator Bi$_{14}$Rh$_3$I$_9$ (top) and local density of states within the inverted band gap showing the protected edge state as marked (bottom).
Chern insulators and their relatives

I will give an introduction to Chern insulators and briefly discuss their interacting and higher-dimensional generalisations, namely fractional Chern insulators and Weyl semimetals.
Abstracts

of posters

in alphabetical order
Spin-freezing in diluted spin ice Dy$_{2-x}$Ca$_x$Ti$_2$O$_7$

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The geometrically frustrated rare earth pyrochlore oxides $R_2^{3+}B_2^{4+}O_7$ in which the $R^{3+}$ ions form a network of corner-sharing tetrahedra, which is the quintessential lattice for geometrical frustration, have created intense research interests because of the novel physics they present owing to a delicate competition between the magnetic exchange, crystal field and dipolar interactions [1]. For example, the combination of crystal field anisotropy and dipolar interactions results in a spin-ice ground state in Dy$_2$Ti$_2$O$_7$ where the fundamental excitations are magnetic monopoles [1-3]. In addition to spin-ice behavior below $\sim 2$ K, Dy$_2$Ti$_2$O$_7$ also shows spin-freezing near $T_f \approx 16$ K [4,5]. The spin-freezing anomaly in Dy$_2$Ti$_2$O$_7$ is enhanced by the application of magnetic field which is quite distinct from the usual spin-freezing in spin glass systems where magnetic field quenches the spin-freezing. We have investigated the effect of nonmagnetic Ca$^{2+}$ substitution for magnetic Dy$^{3+}$ on spin freezing in Dy$_2$Ti$_2$O$_7$. The physical properties of Dy$_{2-x}$Ca$_x$Ti$_2$O$_7$ ($x = 0, 0.1$) have been investigated by ac susceptibility, dc magnetic susceptibility, isothermal magnetization and heat capacity measurements. The ac susceptibility data reveal the strong influence of Ca substitution on spin-freezing at $T_f$. The frequency dependent anomaly in ac susceptibility is substantially weakened by Ca substitution. The effect of nonmagnetic Ca$^{2+}$ substitution on spin-freezing is similar to that of nonmagnetic isovalent Y$^{3+}$ substitution [6], however the suppression of spin-freezing is substantially stronger in Dy$_{1.8}$Ca$_{0.2}$Ti$_2$O$_7$ than in Dy$_{1.8}$Y$_{0.2}$Ti$_2$O$_7$. Cole-Cole analysis of ac susceptibility reveals a single relaxation mode similar to that of undoped Dy$_2$Ti$_2$O$_7$. Hole doping by Ca$^{2+}$ substitution does not bring any noticeable change in the electrical properties, and as revealed by a zero value of the Sommerfeld coefficient of electronic heat capacity, Dy$_{1.8}$Ca$_{0.2}$Ti$_2$O$_7$ also has an insulating ground similar to Dy$_2$Ti$_2$O$_7$. The results of our investigations on Dy$_{1.8}$Ca$_{0.2}$Ti$_2$O$_7$ will be presented in detail.

We study spin ice systems with an applied magnetic field in the [100] direction using a single spin flip algorithm with and additional constraint: the number of magnetic monopoles in the system must be constant throughout the simulation [1]. This constraint allow us to visit only the lowest energy manifold.

As a first approach we study the nearest neighbour model. The interplay between spin correlations and the applied magnetic field produce a singular phase transition with no fluctuations al low temperature. We identify this transition as a Kasteleyn transition and reproduce the previous results obtained with a worm algorithm [2], thus testing the constraint monopoles method.

Finally, we study the effect of dipolar interactions on the Kasteleyn transition. We find a high temperature transition that we identify as a Kasteleyn phase transition. At low temperature and fields less than 0.06T we find two extra phases. One of them was identified with the order phase found by Melko, den Hertog, and Gingras (MHG state) [3]. The other phase was not expected, we identified it with a phase that share characteristics with the saturated state of the Kasteleyn transition and with the MHG state.

References

A new spin-liquid antiferromagnet based on opposite-sign bi-triangles

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Frustration due to competing magnetic exchange interactions can give rise to exotic ground states and excitations. In extreme cases long-range magnetic order is completely suppressed and fluctuations persist down to the lowest temperatures. Here, we present a new candidate compound for such a spin-liquid ground state built on spin-\(\frac{1}{2}\) Cr\(^{5+}\) ions. In Ca\(_{10}\)Cr\(_7\)O\(_{28}\), long-range magnetic order is absent down to a temperature of 19 mK while the excitations are diffuse and gapless as shown by inelastic neutron scattering. Muon spin relaxation and AC susceptibility confirm the absence of static magnetism and reveal that the ground state is fully dynamical.

Ca\(_{10}\)Cr\(_7\)O\(_{28}\) can be driven towards long range ferromagnetic order by applying an external magnetic field of 12 T. In contrast to the zero-field excitations, the excitations in the saturated state resemble sharp magnon modes, and by fitting their dispersions to linear spin wave theory the exchange constants were extracted. A mixture of FM and AFM interactions were found where the FM interactions are greater than the AFM interactions. The coupling scheme consists of bi-triangles where ferromagnetic triangles lie directly over antiferromagnetic triangles and the intertriangle coupling is weakly ferromagnetic (see the figure below where green and red bonds are FM while blue bonds are AFM). The frustration arises from the opposite sign of the coupling within the two triangles and neither triangle can realize its intrinsic spin arrangement due to the intertriangle coupling. This motif forms a 2D bilayer structure where in each layer the AFM triangles are coupled to FM triangles via their corners in a kagome like arrangement. FRG calculations confirm the absence of long-range order and the spin-liquid ground state in this new type of frustrated system.

![Diagram](image-url)
Transverse and longitudinal spinons and their confinement in the quasi-1D XXZ-antiferromagnet SrCo$_2$V$_2$O$_8$


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The study of emergent phenomena in interacting quantum systems is one of the main research topics of condensed-matter physics. Here we report neutron scattering results of the quasi-1D Ising-like antiferromagnet SrCo$_2$V$_2$O$_8$. The spin chains in SrCo$_2$V$_2$O$_8$ are formed by edge-shared CoO$_6$ (Co$^{2+}$; 3$d^7$, effective $S$ =1/2) octahedra along the $c$ axis. In zero field, it orders antiferromagnetically below 5 K. The magnetic structure [characterized by propagation vector $k$ = (0 0 1)] consists of antiferromagnetic (AFM) chains along the $c$ axis, that are arranged ferro-/antiferromagnetically along the $a/b$ axes. In the pure 1D state at ($T > T_N$ =5 K), inelastic neutron scattering reveals a gapped continuum of free spinons (spin-1/2 excitations) that are modeled nicely by the $S$ =1/2 XXZ AFM chain with intrachain interaction constant $J$ =7.0±0.1 meV and anisotropy parameter $\varepsilon$ =0.50±0.02. Below $T_N$, the continuum transforms into a hierarchy of discrete excited states indicating the confinement of the spinon-pairs due to a linear interacting potential imposed by the weak interchain couplings. The sequence of excited states follows the zeros of the Airy function confirming a linear confirming potential. Interestingly, such discrete excitations are found for both the transverse and longitudinal polarizations. The unusual sharp longitudinal modes, which are not observed in the case of ferromagnetic intrachain interactions as in CoNb$_2$O$_6$, are stabilized in SrCo$_2$V$_2$O$_8$ by the antiferromagnetic intrachain interactions.
Dynamical correlations of quantum magnets provide valuable information about the systems under study. Especially at finite temperature, many observation, e.g. in inelastic neutron scattering experiments, are still not quantitatively understood. Generically, the elementary excitations of quantum magnets are hard-core bosons because no two of them can be present at the same site. In our previous work, we used the diagrammatic Brückner approach to deal with complicated, interacting models of hard-core bosons at finite temperature. Specifically, we addressed problems with a single flavor of excitations. In this case, the self-consistent Brückner approach yields very accurate results, e.g., conserved sum rules for a wide range of temperatures. Switching to a higher number of flavors spoils this feature. In our contribution we investigate this phenomenon and discuss the difference to the single flavor case. A deeper understanding of the breakdown might yield an improved view on the finite temperature dynamics of hard-core bosons at finite temperatures. Additionally, we present results for the thermal occupation function of flavored hard-core bosons based on thermodynamical arguments. As far as we know, these results are not yet mentioned in the literature.
Sudden field rotations in spin-ice

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Spin ice systems have a pyrochlore structure, where the magnetically active sites form a lattice of corner-sharing tetrahedra. These moments behave Ising-like at low temperatures, pointing in or out of the elementary tetrahedra. The combination of exchange and dipolar interactions leads an effective ferromagnetic interaction between nearest neighbours and gives origin to ice rules, analog to Bernal-Fowler’s: the two-in two-out configuration is the lowest energy state.

Excitations - defects, i.e., tetrahedra that violate the ice rules - can be considered as magnetic monopoles which can move through the system by flipping magnetic moments. The dynamics of these excitations have already been studied by Castelnovo et al\textsuperscript{1,2}, by monitoring the monopole annihilation process in thermal and field quenches. In both quenches, they found a dynamical arrest that slows the annihilation process and leads to an interesting time-dependence of the monopole density.

We are interested in these dynamics and their experimental measurement. The suggested experiments for detecting monopoles present difficulties due to the short times involved in the density decays compared with the times of thermal and field quenches.

We propose a different point of view: a field quench through a sudden rotation of magnetic field. If a spin ice system is placed in a strong [111] magnetic field, the lowest energy state is one in which every tetraedron has a 3in-1out or 3out-1in configuration. In the saturated regime, the system is a perfect ionic crystal of magnetic monopoles. On the other hand, a [100] magnetic field benefits the magnetic monopole annihilation. In the present work, we studied by Monte Carlo simulations the dynamic behaviour of spin ice under the action of a magnetic field applied in the [100] direction, starting from a magnetic monopole crystal ([111] magnetic field) and turning the field in the [100] direction.

We study the interplay of long-range interactions and quantum fluctuations that is naturally present in a variety of physical systems. Important examples are dipolar interactions in spin ice or long-range forces between cold atoms in optical lattices. Here, we focus on the simplest microscopic model displaying such an interplay which is a long-range Ising interaction in the presence of a transverse magnetic field on a one-dimensional chain. We use perturbative continuous unitary transformations to calculate the groundstate energy per site as well as the low-energy gap inside the polarized phase at zero temperature as a high-order series expansion about the high-field limit.
Doping a topological quantum spin liquid: slow holes in the Kitaev honeycomb model

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We present a controlled microscopic study of mobile holes in the spatially anisotropic (Abelian) gapped phase of the Kitaev honeycomb model. We address the properties of (i) a single hole [its internal degrees of freedom as well as its hopping properties]; (ii) a pair of holes [their absolute and relative particle statistics as well as their interactions]; and (iii) the collective state for a finite density of holes. Our main result is that the holes in the doped model possess internal degrees of freedom as they can bind the fractionalized excitations of the undoped model: composite holes with different excitations bound are distinct fractionalized particles with fundamentally different properties that have different signatures in the physical properties at finite doping. For example: some holes are free to hop in two dimensions, while others are confined to hop in one dimension only; distinct hole types have different particle statistics and, in particular, some of them exhibit non-trivial (anyonic) relative statistics. At finite doping, the respective hopping dimensionalities manifest themselves in an electrical conductivity that is either approximately isotropic or extremely anisotropic.
Electronic transport in graphene with particle-hole-asymmetric disorder

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(Dated: May 13, 2015)

We study the conductivity of graphene with a smooth but particle-hole-asymmetric disorder potential. Using perturbation theory for the weak-disorder regime and numerical calculations we investigate how the particle-hole asymmetry shifts the position of the minimal conductivity away from the Dirac point $\varepsilon = 0$. We find that the conductivity minimum is shifted in opposite directions for weak and strong disorder. For large disorder strengths the conductivity minimum appears close to the doping level for which electron and hole doped regions (“puddles”) are equal in size.

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Study of proton disorder in D2O – ice at the Flat-cone Diffractometer E2

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Water ice (H2O) at low pressure can be understood as a hexagonal structure where each Oxygen atom is bond to two Hydrogen atoms. Further, each bond between Oxygen atoms is occupied by only one Hydrogen atom. These are the famous ice – rules that give rise to a highly disordered ground state with a residual entropy of R Ln (3/2). We have measured the diffuse scattering of a large D2O ice crystal using neutron diffraction at the Flat-cone Diffractometer E2. Different to previous descriptions of the ice - structure by Monte Carlo methods we are able to explain the data using an analytical method. The theoretical approach has been integrated into the data analysis tool TVneXus to fit the complex data sets using GPU computing power.
Highly-frustrated magnets are characterized by a (nearly) flat one-triplet excitation band at zero temperature. Little is known from theoretical studies about the temperature-dependence of this single-particle dispersion and less still concerning multi-particle dynamics at finite temperature. Experimentally, inelastic neutron scattering studies of low-dimensional frustrated systems such as SrCu$_2$(BO$_3$)$_2$ require an interpretation of the thermal evolution of scattering intensities. We investigate these issues using the example of a highly frustrated spin-1/2 ladder. We find that single- and many-particle excitations persist as sharp spectral features in the dynamic structure factor to surprisingly high and even infinite temperatures. In addition, close to a zero-temperature quantum phase transition, low-lying non-magnetic excitations give rise to an unusual low-temperature feature in the specific heat as well as a concurrent anomalously rapid transfer of spectral weight out of the single-particle band to a wide range of energies.
Effective spin-models for strongly correlated electron systems with spin-orbit interaction

Dominik Ixert, Kai Phillip Schmidt

The physics of strongly correlated electron systems is a very promising field of research within condensed matter theory, which can lead to exotic phases like quantum spin liquids. Another fascinating topic is the physics of topological insulators which typically arise from spin-orbit interactions. One fundamental question is now which physical phenomena arise if strong correlations and spin-orbit interactions are present simultaneously. One microscopic model which combines both is the so-called Kane-Mele-Hubbard-model which we will study here at zero temperature and at half filling. The phase diagram consists of a quantum spin Hall insulator for weak correlations and a long-range ordered Mott insulator for strong correlations, both separated by a quantum phase transition in the 3dXY universality class. Since the charge gap is always finite, one might wonder whether it is possible to understand the whole phase diagram including the topological quantum spin Hall insulator from a strong-coupling perspective within an effective spin-model. To this end we apply continuous unitary transformations to separate spin and charge degrees of freedom in order to derive such an effective low-energy description. The effective low-energy spin-model is then analyzed by exact diagonalization.
Nonlinear bond-operator theory and 1/d expansion for coupled-dimer magnets

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For coupled-dimer Heisenberg magnets, a paradigm of magnetic quantum phase transition, we develop a systematic expansion in 1/d, where d is spatial dimension, using bond operators. We apply this technique to a model of dimers on a hyper-cubic lattice, a generalization of the square-lattice bilayer Heisenberg model to arbitrary d. We calculate physical observables at zero temperature in both the quantum paramagnetic and anti-ferromagnetic phases and show that the 1/d expansion consistently describes the entire phase diagram including the quantum critical point. In particular, we determine the dispersion and spectral weight distribution of the elementary excitations, including the amplitude (i.e., Higgs) mode of the anti-ferromagnetic phase.
Effective Models from Matrix Product States

Frederik Keim and G"otz S. Uhrig

March 30, 2015

Abstract

Effective models in second quantization are a powerful tool in understanding the low energy physics of condensed matter systems. Analytical approaches to derive them are, however, limited to special cases. We present a largely unbiased variational method to derive an effective model on the bi-linear level, based on the framework of matrix product states (MPS). Using the transfer matrix method, MPS work very efficiently in the thermodynamic limit for one-dimensional systems. We show how to drive an expression for the local creation operator of the elementary excitation and validate it by using it to compute the spectral weight. We also discuss the progress in and the challenges of taking the approach beyond the bi-linear level.
Dynamical structure factor and Raman scattering of two- and three-dimensional Kitaev spin liquids

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Topological states of matter present a wide variety of striking new phenomena, most prominently is the fractionalization of electrons. Their detection, however, is fundamentally complicated by the lack of any local order. While there are now several instances of candidate topological spin liquids, their identification remains challenging. We provide a complete and exact theoretical study of the dynamical structure factor and the inelastic Raman scattering response of two- and three-dimensional quantum spin liquid phases. Our analysis of dynamical properties of Kitaev models on harmonic-honeycomb lattices identifies new varieties of the venerable X-ray edge problem and explores connections to the physics of quantum quenches. Overall, we show that there are salient signatures of the emergent Majorana fermions and gauge fluxes. We make connection to recent experiments.
Abstract

Topological semimetals – the gapless cousins of topological insulators – have attracted much recent interest. They exhibit bulk features such as gapless Weyl nodes that can be characterized by topological invariants. In addition, they possess gapless surface modes, also called Fermi arcs, which are intimately connected to the bulk features and, thus, topologically protected.

Here we discuss the emergence of such a topological semimetal in three-dimensional generalizations of the Kitaev model. These models describe the fractionalization of spin-orbit entangled moments into Majorana fermions and a $\mathbb{Z}_2$ gauge field. We demonstrate that the Majorana fermions form a Weyl superconductor for the Kitaev model on the recently synthesized hyperhoneycomb structure of $\beta$-Li$_2$IrO$_3$ in the presence of an external magnetic field. We discuss the topologically protected bulk and surface features of this state, which we dub a Weyl spin liquid.
A recent experiment [Nadj-Perge et al., Science 346, 602 (2014)] gives possible evidence for Majorana bound states in chains of magnetic adatoms placed on a superconductor. While many features of the observed end states are naturally interpreted in terms of Majoranas, their strong localization remained puzzling. We consider a linear chain of Anderson impurities on a superconductor as a minimal model and treat it largely analytically within mean-field theory. We explore the phase diagram, the subgap excitation spectrum, and the Majorana wavefunctions. Owing to a strong velocity renormalization, the latter are localized on a scale which is parametrically small compared to the coherence length of the host superconductor.
Ultrasonic investigation of GaV$_4$S$_8$

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Skyrmion lattices, periodic arrays of spin vortices, have recently been observed in various magnets with chiral structure. Most interestingly, in lacunar spinel GaV$_4$S$_8$ novel Néel-type skyrmions, composed of spin cycloids carrying a monopole moment, have been identified. The system undergoes orbital ordering at 44 K and reveals a complex magnetic phase diagram below 13 K, including a ferromagnetic, cycloidal and Néel-type skyrmion lattice phase. Here, we present results of ultrasound investigations performed on a high-quality single crystal of GaV$_4$S$_8$. The temperature dependence of the sound velocity and attenuation shows a huge anomaly at $T_s \sim 44$ K followed by a pronounce feature at $T_c \sim 12.5$ K related to a structural transition and ferromagnetic ordering, respectively. A field-induced transitions at temperatures below $T_c$ reveals a complex magnetic structure of GaV$_4$S$_8$, suggesting a competition of several interactions. Based on these measurements, we mapped out the $B$–$T$ phase diagram of GaV$_4$S$_8$ and discuss the role of the lattice degrees of freedom in this material.

TUNNELING PROCESSES INTO LOCALIZED SUBGAP STATES IN SUPERCONDUCTORS

M. Ruby,¹ F. Pientka,² Y. Peng,² F. von Oppen,² B. W. Heinrich,¹ and K. J. Franke¹

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We combine scanning-tunneling-spectroscopy experiments probing magnetic impurities on a superconducting surface with a theoretical analysis of the tunneling processes between (superconducting) tip and substrate. We show that the current is carried by single-electron tunneling at large tip-substrate distances and Andreev reflections at smaller distances. The single-electron current requires relaxation processes between the impurity-induced Shiba bound state and the quasiparticle continuum, allowing us to extract information on such relaxation processes from our analysis.

Orphan spins in a disordered classical spin liquid. J. Rehn\textsuperscript{1}, A. Sen\textsuperscript{1,2}, A. Andreanov\textsuperscript{3}, A. Scardicchio\textsuperscript{3}, K. Damle\textsuperscript{4}, R. Moessner\textsuperscript{1}. \textsuperscript{1}MPIPKS, Dresden, \textsuperscript{2}IACS, Kolkata, \textsuperscript{3}ICTP, Trieste, \textsuperscript{4}TIFR, Mumbai. — Highly frustrated magnets often exhibit a nontrivial correlated phase at low temperatures while avoiding conventional ordering. This spin liquid phase presents exotic fractionalized thermal excitations with long ranged entropic interactions. An interesting scenario arises by adding nonmagnetic impurities in such systems, as occurs in the material SCGO. In this case the violation of the “ice rules” can happen due to the presence of impurities, giving rise to the so called “Orphan spins” which constitute analogous degrees of freedom to the thermal excitations in the nondiluted system. The effective picture for the diluted system at zero temperature is an instance of a problem described by Euclidean random matrices, and we will present results of the study of this effective picture.
Non equilibrium behavior in spin ice Dy$_2$Ti$_2$O

Andrè Sokolowski (HZB)

This presentation focuses on the spin ice system Dy$_2$Ti$_2$O$_7$ (DTO). The geometrical frustration in these systems inhibits the formation of a single ground state configuration [1], but recent studies reveal a possible onset of an ordered state at very long waiting times [2]. I will present our latest experiments of the out-of-equilibrium (ac susceptibility and heat conductivity) and in-equilibrium (neutron scattering and heat capacity) state of DTO. Furthermore, I will present an outlook to the Stanford-type magnetic monopole detection experiment, which is prepared at the moment.


Spectral functions of one-dimensional quantum magnets

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**LPTM, Université de Cergy-Pontoise, France

We present numerical results for experimentally relevant spectral functions of one-dimensional strongly correlated quantum systems at both zero and finite temperature. As examples, we study the electron spin resonance (ESR) intensity and dynamic spin structure factor of spin-1/2 XXZ Heisenberg chains with Dzyaloshinskii-Moriya interactions in magnetic fields. The spectral functions are computed directly in the frequency domain via a Chebyshev expansion of the Green’s function in a density-matrix renormalization group (DMRG) framework using matrix product states (MPS). At finite temperature, the method is based on a purification of the density operator by exploiting a Liouville space formulation of the dynamics. Our results are discussed in the context of experimentally observed bound states and their field-theoretical descriptions.
Experimental evidence for Majorana bound states largely relies on measurements of the tunneling conductance. While the conductance into a Majorana state is in principle quantized to $2e^2/h$, this quantization is difficult to observe due to thermal broadening in the normal-metal lead. Here, we propose to use a superconducting lead instead, whose gap strongly suppresses the effects of temperature broadening. A Majorana state leads to symmetric conductance peaks at $eV = \pm \Delta$ which have the universal height $G = (4 - \pi)2e^2/h$ for a wide range of tunneling strengths and temperatures. For a superconducting scanning tunneling microscope tip, Majorana states therefore appear as a spatial conductance plateau while the conductance varies with the local wavefunction for a trivial fermionic bound state. We also discuss effects of nonresonant (bulk) Andreev reflections and quasiparticle poisoning.
Ultracold dipolar gases modelled using pseudopotentials

T.M. Whitehead and G.J. Conduit

\[ \text{Cavendish Laboratory, J.J. Thomson Avenue, Cambridge, CB3 0HE, United Kingdom} \]

A gas of ultracold molecules offers a highly controlled environment in which to study strongly correlated systems in the presence of the long-range dipolar interaction. However, at particle coalescence the divergent \( 1/r^3 \) dipolar potential and associated pathological wavefunction hinder computational analysis. To overcome these numerical difficulties we propose a pseudopotential for the dipolar interaction in two dimensions that is explicitly smooth at particle coalescence, offering an 18-times speedup in high-accuracy Diffusion Monte Carlo calculations.
Long-range order and spin-ice-like fluctuation in pyrochlore \( \text{Nd}_2\text{Zr}_2\text{O}_7 \)

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Geometrically frustrated magnetic materials are ideal candidates for exhibiting large quantum mechanical spin fluctuations and the emergence of novel magnetic ground states. Over the past 20 years, many interesting and often exotic magnetic and thermodynamic phenomena have been observed in the Pyrochlore oxides which consist of highly frustrated corner-sharing tetrahedra, such as dipolar spin ice, quantum spin ice, spin liquid and spin glass. [1] Most of the studies were concentrated on the heavy Rare Earth titanate Pyrochlores which have large moments, like \( \text{Dy}_2\text{Ti}_2\text{O}_7 \), \( \text{Ho}_2\text{Ti}_2\text{O}_7 \) and \( \text{Tb}_2\text{Ti}_2\text{O}_7 \).[2–4] Here we investigate the light Rare Earth Zirconate Pyrochlore, \( \text{Nd}_2\text{Zr}_2\text{O}_7 \), using bulk properties measurements and neutron scattering. \( \text{Nd}_2\text{Zr}_2\text{O}_7 \) orders antiferromagnetically below 0.4K and has a negative Curie-Weiss temperature of \(~27\text{K}\) and effective moment of \( \mu_{\text{eff}}=3.4\mu_\text{B}/\text{Nd} \). It orders in the ‘all-in-all-out’ magnetic structure but with a much reduced Nd moment of \( \mu_{\text{B}}=1.2\mu_\text{B} \) at 0.1K (compared to \( 3.3\mu_\text{B} \) expected for full ordering). Inelastic neutron scattering indicates that there is a large gap (\(~23\text{meV}\)) between the ground state and the first crystal field excitation state and thus strong Ising anisotropy is expected. The pinch point which is characteristic for spin ice, is also present in our neutron diffuse scattering data both below \(~0.3\text{K}\) and above \(~0.45\text{K}\) \( T_N \). This may be because above \( T_N \) it is a cooperative paramagnet with powder-law spin correlations due to dipolar interactions and even below the ordered state, more than 2/3 of the full moment is still fluctuating.

References:
## List of participants of the Helmholtz Virtual Institute Workshop

"New states of matter and their excitations"

June 16, 2015 - June 19, 2015, Berlin-Adlershof

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