WORKSHOP

QUANTUM MAGNETS 2015

KOLYMPARI, CRETE

13-19 SEPTEMBER 2015

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1. PREFACE

The focus of this workshop will be on a wide range of recent developments at the forefront of research in quantum magnetism. It is organized by the "Crete Center for Quantum Complexity and Nanotechnology" and brings together leading experts in this field, following the spirit of the previous NOVMAG workshop "Transport phenomena in low dimensional quantum magnets', held in September 2010 and LOTHERM workshop "Quantum Magnets 2013, Advances in Quantum Magnets - Dynamics", held in September 2013.

Topics of the Workshop include:

- quantum spin chains and ladders
- transport and dynamics
- skyrmions
- spin ice
- spin liquids
- frustrated magnets
- iridates, new materials
- magnonics

The program features invited talks as well as poster presentations.

This workshop is supported by the European Commission through the CCQCN project (REGPOT-2012-2013-1, grant agreement no: 316165).

We are grateful to all participants who are willing to share their recent results and we hope you will enjoy the workshop as well as your stay in Kolympari.

Xenophon Zotos, University of Crete, Greece
Christian Heß, IFW Dresden, Germany
Paul van Loosdrecht, Universıty of Cologne, Germany

2. TIMETABLE

Time	Sunday, 13 September 2015
19:00	Registration and welcome reception
21:00	*Dinner*

	Monday, 14 September 2015
08:40-09:00	**Welcome address and introduction**
	Session 1: Transport & Dynamics **Chair: X. Zotos**
09:00-09:45	**1.1 A. Kluemper** "On the finite temperature Drude weight of the spin-1/2 XXZ Heisenberg chain"
09:45-10:30	**1.2 T. Lorenz** "Quantum Phase Transitions in XXZ Spin-1/2 Chain Materials"
10:30-11:00	*Coffee break*
	Session 1: (continued)
11:00-11:45	**1.3 R. Steinigeweg** "Quantum typicality: A novel numerical approach to dynamics and thermalization"
11:45-12:30	**1.4 A. Mohan** "Thermal transport in a two-dimensional spin-1/2 Heisenberg antiferromagnet compound: Shedding light on scattering mechanisms"
12:30-13:00	**1.5 C. Psaroudaki** "Spin and magnetothermal transport in the S = 1/2 XXZ chain"
13.00-16:00	*Lunch break*
	Session 2: (continued) **Chair: C. Hess**
16:00-16:45	**2.1 V. Bisogni** "Probing spin interactions in edge-shared and corner-shared 1D cuprate chain systems by Resonant Inelastic X-ray Scattering"
16:45-17:30	**2.2 J. Moeller** "Organic quantum magnets under pressure"
17:30-18:15	**Short poster presentations**
18:30-20:30	Poster session with wine and snacks
20:30	*Dinner*

	Tuesday, 15 September 2015
	Session 3: Novel Quantum Magnets **Chair: P. Prelovsek**
09:00-09:45	**3.1 H. Aoki** "Designing flat-band ferromagnets - a path to make organic-based systems magnetic and topological"
09:45-10:30	**3.2 A. Chernychev** **"**Quantum order-by-disorder and excitations in anisotropic Kagome-lattice antiferromagnets"
10:30-11:00	*Coffee break*
	Session 4: Far out of equilibrium
11:00-11:45	**4.1 S. Caux** "Dynamics and relaxation in integrable quantum spin chains"
11:45-12:30	**4.2 T. Oka** "Floquet theory of laser-induced phase transitions and applications to quantum magnets"
12:30-13:00	**4.3 J. Herbrych** “Light induced magnetization in a spin S=1 easy - plane antiferromagnetic chain"
13:00-14:00	*Lunch break*
	Excursion and Cretan Dinner

	Wednesday, 16 September 2015
	Session 5: Magnonics **Chair: C. Hess**
09:30-10:15	**5.1 B. Hillebrands** "Magnon supercurrents"
10:15-11:00	**5.2 D. Gruendler** "Collective spin excitations in ferri- and helimagnets containing nanoscale magnetic structures and Skyrmions"
11:00-11:30	*Coffee break*
	Session 6: Frustrated Magnetism
11:30-12:15	**6.1 C. Broholm** "Spin-Peierls-like Phase Transitions in Materials with Competing Exchange Interactions"
12:15-13:00	**6.2 C. Batista** "Charge effects and thermoelectric behavior in frustrated Mott Insulators"
13:00-16:00	*Lunch break*
	Session 7: (continued) **Chair: T. Lorenz**

16:00-16:45	**7.1 J. Hemberger** "Critical speeding-up in the magnetoelectric response of spin-ice near its monopole liquid–gas transition"
16:45-17:30	**7.2 P. Prelovsek** "Dynamics and ordering in random spin chains"
17:30-18:00	*Coffee break*
18:00-18:45	**7.3 S. Zvyagin** "Spin dynamics in triangular-lattice antiferromagnets: high-field ESR studies"
18:45-19:15	**7.4 A. Briffa** “$Er_2Ti_2O_7$: a fight between crystal fields and quantum fluctuations”
20:30	*Dinner*

	Thursday, 17 September 2015
	Sesion 8: Novel Quantum Magnets Chair: A. Kluemper
09:00-09:45	**8.1 I. Affleck** "Phase diagram of the interacting Majorana chain"
09:45-10:30	**8.2 H. Tsunetsugu** "Spin singlet order in breathing pyrochlore"
10:30-11:00	*Coffee break*
	Session 8: (continued)
11:00-11:45	**8.3 A. Rosch** "Skyrmions in chiral magnets"
11:45-12:30	**8.4 Zhe Wang** "Fractional Spinonic Excitations in a 1D Quantum Antiferromagnet SrCo2V2O8"
12:30-13:15	**8.5 J. Knolle** "Dynamics of a Quantum Spin Liquid"
13.15 -16:00	*Lunch break*
	Session 9: Transport and Dynamics Chair: X. Zotos
16:00-16:45	**9.1 F. Heidrich-Meissner** "Transport in spin ladders and the Hubbard model"
16:45-17:30	**9.2 M. Montagnese** “Accessing Phonon-magnon interaction in low dimensional quantum magnets through dynamic heat transport measurements”
17:30–18:00	*Coffee break*
	Alex Revcolevschi "Review of several decades of crystal growth, characterization and a few physical properties of correlated electron oxide crystals"
20:30	*Dinner*

	Friday, 18 September 2015
	Sesion 9: Model Systems **Chair: P. Prelovsek**
09:00-09:45	**10.1 S. Otte** "Atomic spin chains as testing ground for quantum magnetism"
09:45-10:30	**10.2 Y. Bunkov** "Spin superfluidity and magnon BEC"
10:30-11:00	*Coffee break*
	Sesion 10: (continued)
11:00-11:45	**10.3 I. Kiritsis** "Ballistic conductivities and the AdS/CFT correspondence"
11:45-12:30	**10.4 S.-W.-Cheong** "ZmxZn Topology of Domains and Domain Walls"
13.00	*Lunch*
	Farewell

3 ABSTRACTS OF TALKS

Phase diagram of the interacting Majorana chain

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A lattice of Majorana fermions arises as a model for some topological materials. I will analyze the simplest one dimensional version of this model with interactions included. It has a rich phase diagram including a phase with emergent supersymmetry.

Designing flat-band ferromagnets - a path to make organic-based systems magnetic and topological

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Flat-band ferromagnetism, conceived by Lieb, by Mielke and by Tasaki in the 1980-90's is a unique mechanism in that the magnetism arises from an unusual “Wannier" orbits rather than the mere flatness of the band. While we have earlier proposed an organic 1D polymer (connected polygons) as a candidate, if we systematically look for two-dimensional (2D) materials we can go back to graphene with antidot arrays proposed by Shima and Aoki back in the 1990's, which accommodate a systematic occurrence of flat band, along with Dirac cones, for a group-theoretical reason. The system, nowadays dubbed carbon nanomesh, is attracting renewed interests.

In this talk I shall introduce our most recent proposal, inspired by Shima-Aoki scheme, designed for a new kind of organic nanomesh, i.e., 2D metal-organic frameworks (MOFs). The designed MOF has a virtue that flat bands arise right around the Fermi energy, and the flat-band ferromagnetism is indeed confirmed to arise for the right choice of materials with the spin-density functional. In the presence of a spin-orbit interaction arising from metallic atoms, the system can even become a topological insulator. Thus organic materials can open a unique avenue for designing magnetism.

The work on the MOF is a Tokyo-MIT collaboration with Masahiko Yamada, Tomohiro Soejima, Naoto Tsuji, Daisuke Hirai and Mircea Dinca.

Charge effects and thermoelectric behavior in frustrated Mott Insulators

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Geometrically frustrated Mott insulators can exhibit unexpected charge effects like spontaneous circular electric currents that result from certain (scalar) chiral spin orderings or non-uniform electronic charge distributions associated with a subclass of bond orderings. We will see how these phases can appear in simple Hubbard models and lead to strong magneto-electric effects of pure electronic origin. Moreover, just based on symmetry considerations, we will see that the effective electric and energy current density operators are both related to the local scalar spin chirality. This connection between both operators has interesting physical consequences, such as the possibility of inducing orbital moments with a heat current or observing Nerst and Ettingshausen effects in Mott insulators.

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[2] S-Z Lin and C. D. Batista, Phys. Rev. Lett. **111**, 166602 (2013).

Probing spin interactions in edge-shared and corner-shared 1D cuprate chain systems by Resonant Inelastic X-ray Scattering

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Resonant Inelastic X-ray Scattering (RIXS) is emerging as a novel method for investigating spin excitations. It has recently been demonstrated that Cu-L_3 RIXS is a new powerful experimental tool to map magnon dispersions in the high-T_c cuprates as well as in their parent compounds [1]. Therefore, in systems whit strong magnetic coupling, RIXS can be considered as a complementary technique to inelastic neutron scattering (INS), with high sensitivity to small sample volumes or even thin films. In the proposed talk, two different cases will be discussed, demonstrating that spin interaction can be accessed even well below the energy resolution.

$CuGeO_3$ and Li_2CuO_2 are 1D edge-shared chain systems with frustrated and weak magnetic interactions (< 50 meV) [2,3]. The present energy resolution of RIXS unfortunately prevents from directly probing dispersing excitations below ~ 50-100 meV. However, it is possible to circumvent this limitation by using a charge transfer exciton as a probe. Local spin fluctuations at excitation energies of the order of 1 meV can be detected in this way with great sensitivity by tracking the temperature evolution of the Zhang-Rice exciton [4]. This new method provides a veritable tool to characterize the spin short-range order in frustrated one-dimensional materials.

$CaCu_2O_3$ is a two-leg ladder compound consisting of two coupled corner-shared spin chains. Because of its buckled geometry, however, a clear spinon dispersion is directly detected in the low energy portion of the RIXS spectra, as in an ideal 1D spin chain system [5,6]. A detailed analysis of the two-spinons excitations is presented showing indeed how RIXS is sensitive to the time dynamics of the magnetic excitations [7].

[1] L.J.P. Ament et al., Review of Modern Physics **83**, 705 (2011)
[2] M. Hase et al., Physical Review Letter **70**, 3651 (1993)
[3] W. E. A. Lorenz et al., Europhysics Letter **88**, 37002 (2009)
[4] C. Monney, V. Bisogni et *al*., Physical Review Letter **110**, 087403 (2013)
[5] B. Lake et al., Nature Physics **6**, 50 (2010).
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[7] V. Bisogni et al., Physical Review Letter **112**, 147401 (2014)

$Er_2Ti_2O_7$: a fight between crystal fields and quantum fluctuations

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Using the previously published neutron scattering experiments we deduce that $Er_2Ti_2O_7$ magnetically orders tetragonally into a broken-symmetry multiple-q state. Surprisingly, the ordered moments do not to lie close to the crystal-field anticipated directions. We suggest that the low energy gapless mode, visible in specific-heat measurements, is not the usual transverse isotropic Goldstone-mode. It is longitudinal and is associated with the internal transfer of intensity between distinct magnetic Bragg spots.

Spin-Peierls-like Phase Transitions in Materials with Competing Exchange Interactions

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I discuss several examples of phase transitions in highly frustrated spin systems that alter the magnetic exchange interactions to produce a lower energy state. Examples include structural transitions that relieve frustration to superconductors where a large change in magnetic exchange energy is associated with the development of superconductivity. Neutron scattering is used to characterize the different magnetic excitations above and below the transitions and to determine the associated changes in magnetic exchange energy.

Spin superfluidity and magnon BEC

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The magnon BEC, the coherent state of macroscopic number of magnons, manifests itself by coherent precession of magnetization even in an inhomogeneous magnetic field. It was observed, for the first time, in superfluid 3He-B in 1984 1. The magnon BEC has many similarities with the atomic BEC. But it shows a great variety of properties in a different magnetic materials. The magnon BEC demonstrates all the properties of magnetic superfluidity. There were observed: The phase-slip processes at the critical spin current; spin current Josephson effect; spin current vortex; Goldstone modes and other superfluid phenomena. There was observed 6 different states of magnon BEC in superfluid ^{3}He. The comprehensive review of different aspects of magnon BEC in superfluid ^{3}He may be found in resent reviews [2]. The magnon BEC has been found also in a few other spin systems with non-linear magnetic resonance [3].
Here we will classify the different types of magnon BECs.

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2. Bunkov Yu.M., Volovik G.E. (2013) ”Spin superfluidity and magnon BEC” in ”Novel Superfluids” ed. K. H. Bennemann and J. B. Ketterson, Oxford University press.
3. Bunkov Yu. M., Alakshin E. M., Gazizulin R. R. et al. (2012) Phys. Rev. Lett. 108, 177002.

Dynamics and relaxation in integrable quantum spin chains

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This talk will review a number of integrability-based results on the dynamics of quantum spin chains. In equilibrium, space- and time-dependent spin-spin correlations will be reviewed, together with corresponding experimental observations. Integrability also allows to describe the dynamics of (quasi)solitonic excitations and their scattering properties. For more generic out-of-equilibrium situations, a number of recent developments will be explained, including the Quench Action method for explicitly calculating the relaxation of observables after a quantum quench. The exact solution to the Néel-to-XXZ quench using the QA will be presented, together with recent results on the necessity to include quasilocal charges in the Generalized Gibbs Ensemble in order to properly describe post-quench steady-state properties.

ZmxZn Topology of Domains and Domain Walls

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Ordering of charge/spin/orbital degrees of freedom in complex materials accompanies domains and domain walls associated with the directional variants (Zm) and also antiphases (Zn). It has been recently realized that nontrivial ZmxZn topology can exists in large-scale real-space configurations of domains and domains walls of complex materials. Furthermore, the vertices where domain walls merge can be considered as topological defects with well-defined vorticities (Zl vortices). We will discuss the recently-discovered examples of ZmxZn domains and Zl vortices in complex materials.

Quantum order-by-disorder and excitations in anisotropic Kagome-lattice antiferromagnets

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I will report on a recent advance in theoretical understanding of quantum effects in kagome-lattice antiferromagnets and will provide some insights into the quantum order-by-disorder mechanism, important for the broad class of frustrated spin systems. Our recent work challenges general expectations and presents a rare example of quantum order-by-disorder effect yielding the ground state that is different from one favored by thermal fluctuations. We also demonstrate that the order selection is generated by topologically non-trivial tunneling processes, making loops around elementary hexagons. Further progress is made in understanding spectral properties of realistic kagome-lattice antiferromagnets such as Fe-jarosite, for which we demonstrate a remarkable wipe-out effect for a significant portion of their spectrum. This phenomenon is related to the existence of the so-called "flat mode", a ubiquitous feature of the kagome-lattice and other highly-frustrated antiferromagnets, and is due to decay processes involving two of such modes.

Collective spin excitations in ferri- and helimagnets containing nanoscale magnetic structures and Skyrmions

D. Grundler

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Collective spin excitations in magnets exhibiting sub-100 nm wavelength might provide beyond CMOS functionality and advance today's data handling in computationally demanding tasks via parallel processing in cellular networks [1]. Here, insulating magnets are in particular interesting as they offer low spin-wave damping.

We report on spin excitations in insulating ferri- and helimagnetic oxides, i.e., thin films of yttrium iron garnet (YIG) and bulk Cu2OSeO3. We used broadband spin-wave spectroscopy based on coplanar waveguides and a vector network analyzer operated up to 26.5 GHz. For YIG we found that 20-nm-thick films offer a macroscopic damping length of up to almost the mm length scale at room temperature [2]. Based on this material, we show how to excite exchange-dominated spin waves by making use of the grating coupler effect [3] and periodic modulation of the magnetic properties via magnetic nanostructures.

As a cubic chiral helimagnet with space group P213, Cu2OSeO3 supports a Skyrmion lattice at low temperatures that provides periodically modulated magnetic properties by itself. The lattice constant is on the order of 100 nm. Using cryogenic spectroscopy we have studied the collective spin excitations throughout the complete magnetic phase diagram and found a universal behavior of the collective spin excitations when comparing Cu2OSeO3 with other chiral helimagnets [4,5]. By modifying the shape of such materials we show how to vary the eigenfrequencies and spectral weights of the modes. Once stabilized in thin films at room temperature, the Skyrmion lattice might provide novel perspectives for spintronics and nanomagnonics [5,6].

The results were obtained in cooperation with A. Anane, A. Bauer, H. Berger, R. Bernard, P. Bortolotti, F. Brandl, V. Cros, O. d'Allivy Kelly, M. Garst, F. Heimbach, R. Huber, F. Lisiecki, C. Pfleiderer, Haiming Yu, T. Schwarze, I. Stasinopoulos, J. Waizner, and S. Weichselbaumer. Financial support by the German Cluster of Excellence 'Nanosystems Initiative Munich (NIM)', the DFG via project GR1640/5 in the priority programme SPP1538 and via TRR80 is gratefully acknowledged.

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[4] Y. Onose et al., Phys. Rev. Lett. 109, 037603 (2012)
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Transport in spin ladders and the Hubbard model

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There is a continued interest in the transport properties of spin ladders, due to their experimental realizations in both quantum magnets and with ultra-cold atomic gases in optical lattices. These two physical systems motivate different generic spin Hamiltonians: Heisenberg exchange in the former, XY-type of exchange in the latter. This talk will give an overview over the results of recent numerical studies of spin and thermal transport in spin ladders. By generalizing the Hamiltonian, we can also simulate the 1D Hubbard model as a two-leg spin ladder with XY exchange along the legs and Ising-interactions on the rungs. We compute the thermal conductivity of the Hubbard model in this language and confirm its ballistic nature related to non-trivial conservation laws. We compare the results for the thermal Drude weight of the Hubbard chain to the known results for the 1D Heisenberg model.

Critical speeding-up in the magnetoelectric response of spin-ice near its monopole liquid–gas transition

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In systems with competing interactions frustration can create complex ground states with exotic excitations. Spin-ice is a solid manifestation of such a degenerate ground state in which magnetic degrees of freedom carry zero point entropy in analogy water ice[1]. Recently it has been found that excitations in spin-ice behave like magnetic monopoles[2]. In a magnetic field along [111] direction the density of these monopoles is a function of temperature and magnetic field and the corresponding phase diagram exhibits a phase transition which resembles the gas-liquid. Accordingly there exists a critical end-point for the monopole condensation[3]. It also has been postulated that the emergent magnetic monopoles in addition carry electric dipole moments[4].

Using dielectric spectroscopy we demonstrate the existence of such an electric dipole moment coupled to magnetic monopole excitations. Furthermore we are able to examine the monopole dynamics via this magnetoelectric coupling. We can track the relaxation time of the electrically dipolar contribution down to low temperatures in the mK-range as a function of an external magnetic field along the crystalline [111] direction. Analyzing the dynamics at temperatures above the critical end-point we see the crossover from the conventional slowing down of the fluctuation dynamics to a critical speeding up[5].

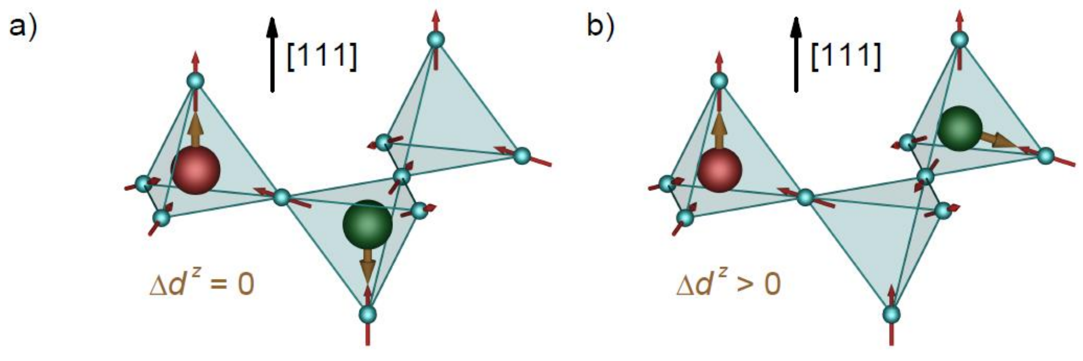

Figure 1: Magnetic and dielectric configuration of monopoles in the corner sharing network of Dy-tedrahedra. Red arrows denote the Dy-spins, yellow arrows denote the induced dielectric dipole moments connected to the magnetic mono- and anti-monopoles (red and green balls). The hopping a) to b) of the "green" monopole corresponds to the flipping of the connective spin between the two tetrahedra and results in a non-vanishing net electric dipole moment Δd^z along the field direction.

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Light induced magnetization in a spin S=1 easy - plane antiferromagnetic chain

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The time evolution of magnetization induced by circularly polarized light in a S=1 Heisenberg chain with large, easy–plane anisotropy is studied numerically and analytically. Results at constant light frequency are interpreted in terms of absorption lines of the electronic spin resonance spectrum. Applying a time dependent light frequency, so called chirping, is shown to be an efficient procedure in order to obtain within a short time a large, controlled value of the magnetization . Furthermore, comparison with a 2-level model provides a qualitative understanding of the induced magnetization process. On the base of: arXiv: cond-mat/1505.03004

Magnon supercurrents

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Magnons, the quanta of spin waves, are bosons and can form a Bose-Einstein condensate (BEC) – a spontaneous coherent ground state – established independently of the magnon excitation mechanism even at room temperature [1]. The Bose-Einstein condensate of magnons has zero group velocity and, thus, it cannot be directly used for information transport.

However, a collective motion of condensed magnons driven by a phase gradient of a condensate wavefunction – magnon supercurrents – are the most promising candidates for the utilization of magnon macroscopic quantum phenomena at room temperature for spin information transport and processing.

The dynamics of the magnon BEC in a thermal gradient, which was revealed by means of time- and wavevector-resolved Brillouin light scattering (BLS) spectroscopy, presents the first evidence of the formation of a magnon supercurrent. It has been found that the decay of a freely evolving magnon BEC, which spontaneously forms in a parametrically driven, single-crystal film of yttrium iron garnet (Y3Fe5O12, YIG) [2], increases with the increase of the thermal gradient created by a probing laser beam. At the same time, the dynamics of the rest of the magnon gas including the parametrically injected and thermalized non-coherent magnons is undisturbed by the heating. Thus, the excessive decay of the BEC can be associated with the outflow of condensed magnons from the laser focal point due to the phase difference induced in the BEC wave function by a temperature gradient. This conclusion is supported by that fact that a uniform sample heating does not affect the BEC decay time.

Experimental data on an augmented magnon BEC contribution to the dc voltage in YIG|Pt heterostructures complement these studies. This phenomenon is attributed to the coherency of the condensed state, and thus we prove, that the coherency of the ground state, needed to establish a supercurrent, can be detected and potentially used in a spin based data transfer using the inverse spin Hall effect.

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Ballistic conductivities and the AdS/CFT correspondence

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In many magnetic condensed matter systems, strongly-interacting electrons are responsible for several exotic physical phenomena.
In gauge theories with a large number of colors/species, a novel technique/duality (known as the AdS/CFT or the holographic correspondence) has been developed to deal with strong interactions at both zero and finite density.
Such techniques put forth infinite new classes of quantum critical points in 2 (and more) spatial dimensions, some with rather exotic behavior.
I will describe some novel properties associated with such strongly coupled theories associated to conductivity and the lessons we draw for more general systems.

On the finite temperature Drude weight of the spin-1/2 XXZ Heisenberg chain

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Despite its integrability, many properties of the S=1/2 Heisenberg spin chain are unknown. Notoriously difficult are transport problems. A very specific, but unsolved problem is the calculation of the weight of the zero frequency delta function peak of the dynamical conductivity of the spin current, also known as the spin Drude weight, at finite temperature.

I will present a consistent approach based on functional equations leading to non-linear integral equations that allow to calculate the energy level curvatures of typical eigenstates at arbitrary temperature T and system size L.

Dynamics of a Quantum Spin Liquid

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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. Here, we address one of the key questions: How can a quantum spin liquid phase be diagnosed in experiments?
We find that the dynamical response can serve as a valuable tool for diagnosing quantum spin liquids. We provide a complete and rarely available exact theoretical study of the dynamical structure factor and the inelastic Raman scattering response of a two- and three-dimensional quantum spin liquid in Abelian and non-Abelian phases. We show that there are salient signatures of the Majorana fermions and gauge fluxes emerging in Kitaev's honeycomb models. Our analysis identifies new varieties of the venerable X-ray edge problem and explores connections to the physics of quantum quenches. A number of proposals suggest that some materials with strong spin-orbit coupling, e.g. {Na/Li}2IrO3 or α-RuCl3 compounds, realize some of the physics of the Kitaev model. We discuss the current experimental situation and recent measurements.

Quantum Phase Transitions in XXZ Spin-1/2 Chain Materials

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Compounds containing low-dimensional spin systems with weak magnetic coupling constants are ideal candidates to test theoretical predictions for the generic behavior close to quantum phase transitions. In this talk, I will discuss the thermodynamic properties of the spin-1/2 chain materials $Cu(C_4H_4N_2)(NO_3)_2$ (or CuPzN) and $Cs_2Co_2Cl_4$. CuPzN is a realization of the isotropic spin-1/2 Heisenberg chain with a weak exchange of J~10 K, such that magnetic fields of about 14 Tesla are sufficient to reach full saturation of the magnetization. The experimental signatures of the corresponding quantum phase transitions are compared in detail to the expectations of the spin-1/2 Heisenberg chain, which is one of the rare theoretical models that can be solved exactly. $Cs_2Co_2Cl_4$ is iso-structural to $Cs_2Cu_2Cl_4$, which is intensely studied due to its 2-dimensional frustrated spin-1/2 magnetism of the Cu^{2+} ions. In this Co-based material, the Co^{2+} ions carry spin 3/2, the magnetic exchange is predominantly 1-dimensional and due to crystal-field effects a pronounced easy-plane magnetic anisotropy is present. Thus, Cs_2CoCl_4 represents the effective spin-1/2 XXZ chain, which is close to the XY limit. An in-plane magnetic field breaks rotational symmetry and induces a quantum phase transition that is located around 2 Tesla in Cs_2CoCl_4 [1]. Finite inter-chain couplings, however, induce 3-dimensional ordering at lowest temperatures and complex phase diagrams of various ordered phases evolve below about 250 mK [2].

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Organic quantum magnets under pressure

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We discuss several spectacular examples of pressure-induced quantum phase transitions in low-dimensional organic quantum magnets. Organic systems offer “soft” molecular frameworks and more accessible energy scales compared to inorganic oxides and thus enable a strong coupling between lattice and magnetism, providing a fruitful playground for exploring quantum critical physics. We will focus on the pressure-induced quantum phase transition in the frustrated quantum spin liquid piperazinium hexachlorodicuprate (PHCC). Recent μSR experiments on PHCC have shown the existence of a quantum critical point (QCP) around 4.3 kbar separating the low-pressure quantum spin liquid from high-pressure magnetically ordered phases [1]. This work was in contradiction with previous inelastic neutron scattering (INS) experiments [2] which observed no closing of the gap in this pressure range. In very recent INS experiments, we have observed gapless Goldstone modes in the dynamic structure factor at 9 kbar [3]. This is in good agreement with the μSR findings and the presence of a pressure-induced quantum critical point at moderate pressure [1]. We suggest an explanation for the apparent contradiction with the previous INS study [2]. Our discussion on PHCC will be complemented with other recent examples from our group concerning the study of QPTs in a number of organic quantum magnets using a range of techniques. This includes in particular work on bond-disordered $NiCl_{2-2x}Br_{2x}$ _ $4SC(NH_2)_2$ with x = 0:06 [4].

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Thermal transport in a two-dimensional spin-1/2 Heisenberg antiferromagnet compound: Shedding light on scattering mechanisms†

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Elementary spin excitations in low-dimensional spin-1/2 magnets have been of interest ever since the era of Ernst Ising and Hans Bethe, when spin models were toyed with. Since then, a multitude of phenomena in many kinds of one- and two-dimensional magnets, due to the quantum nature of these excitations have been realized both theoretically and experimentally. The conduction of heat is one such phenomenon which is governed by the properties of excitations present in a spin system. Heat transport experiments therefore serve as a valuable probe to study the properties of low-energy excitations, and deliver crucial information regarding their scattering processes.

Among many synthesizable compounds that realize different low-dimensional spin arrangements, La_2CuO_4 is a well-known approximation of the two-dimensional spin-1/2 Heisenberg antiferromagnet model. It has been established that in this compound the thermal conductivity has a large contribution due to the propagation of spin excitations in addition to that due to the excitations of the lattice, i.e. phonons [1]. In the talk, I shall revisit thermal transport in La_2CuO_4 by presenting recent thermal conductivity measurements on high quality single crystals of this compound in an unprecedented wide temperature range, and discuss how this data reveals the need for a deeper understanding of the involvement of spin excitations in heat transport; in particular the scattering processes that they take part in by interacting with other excitations present in a system.

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†This work has been carried out in IFW Dresden, Germany.

Accessing Phonon-magnon interaction in low dimensional quantum magnets through dynamic heat transport measurements

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TBA

Floquet theory of laser-induced phase transitions and applications to quantum magnets

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The effect of strong laser on the topology of many body systems is becoming a hot topic [1,2,3]. A theoretical proposal was made in two dimensional Dirac systems where an application of circularly polarized light was shown to turn the system into a quantum Hall state [1,2]. One can see this as a dynamical realization of the Haldane model of a quantum Hall state without Landau levels [4]. This effect can be understood with the help of the Floquet theory of driven quantum systems, where the circularly polarized light plays the role similar to the “next nearest hopping with a nontrivial phase factor” in the Haldane model. Floquet theory can be applied to quantum magnets as well. Using a unitary transformation, one can show that a rotating magnetic field induces an effective magnetic field perpendicular to the rotation plane. One can use this to realize the “laser induced magnetization curve” [5], where the effective magnetic field can be very strong. It becomes even more interesting if we apply laser to multiferroic systems. For example, assuming that the Kitaev honeycomb model is realized, and has miltiferroic coupling, i.e., coupling between polarization and spin, we can realize a topological gapped spin liquid with a laser controllable gap [5].

* This work was mostly done in collaboration with M. Sato and S. Takayoshi.

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Atomic spin chains as testing ground for quantum magnetism

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The field of quantum magnetism aims to capture the rich emergent physics that arises when multiple spins interact, in terms of elementary models such as the spin-1/2 Heisenberg chain. Experimental platforms to verify these models are rare and generally do not provide the possibility to detect spin correlations locally. In my lab we use low-temperature scanning tunneling microscopy to design and build artificial spin lattices with atomic precision. Inelastic electron tunneling spectroscopy enables us to identify the ground state and probe spin excitations as a function of system size, location inside the lattice and coupling parameter values. Two types of collective excitations that play a role in many dynamic magnetic processes are spin waves (magnons) and spinons. Our experiments enable us to study both types of excitations. First, we have been able to map the standing spin wave modes of a ferromagnetic bit of six atoms, and to determine their role in the collective reversal process of the bit [1]. More recently, we have crafted antiferromagnetic spin-1/2 XXZ chains, which allow us to observe spinon excitations, as well as the stepwise transition to a fully aligned phase beyond the critical magnetic field. These findings create a promising experimental environment for putting quantum magnetic models to the test.

[1] A. Spinelli et al., Nature Materials 13, 782 (2014)

Dynamics and ordering in random spin chains

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Recent NMR and μSR experiments on antiferromagnetic spin-chain materials stimulated renewed interest in random-bond quantum models. With the central concept being random singlets we present the numerical analysis confirming a large span of local spin relaxation times and their anomalous temperature dependence. A weak interchain exchange coupling in such systems leads to a long range antiferromagnetic order, as also observed experimentally. Theoretical results for the ordering temperature as well as for local moments and their probability distribution in quasi-1D systems will be shown. The most pronounced effect of the randomness in this case is the large span of local magnetic ordered moments, becoming wider with decrasing interchain coupling. Another challenging aspect in connection with random spin chain is the possibility of many-body localization which will be considered in the classical version of the spin chain.

Spin and magnetothermal transport in the S = 1/2 XXZ chain

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We present a temperature and magnetic field dependence study of spin transport and magnetothermal corrections to the thermal conductivity in the spin S = 1/2 integrable easy-plane regime Heisenberg chain, extending an earlier analysis based on the Bethe ansatz method. We critically discuss the low temperature, weak magnetic field behavior, the effect of magnetothermal corrections in the vicinity of the critical field and their role in recent thermal conductivity experiments in 1D quantum magnets.

Review of several decades of crystal growth, characterization and a few physical properties of correlated electron oxide crystals

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Materials and crystals preparation are key issues in the study of physical properties of compounds. The author will present a review of several decades of crystal growth experiments carried out in his solid state chemistry laboratory, together with characterization and physical properties studies in various correlated electron oxide systems. The crystal growth method used is mainly the image-furnace floating-zone technique which he developed years ago and which is largely used today in many laboratories all over the world to grow high quality pure cm-size crystals.

Dozens of systems have been studied over the years and experiments have mostly concerned oxides such as low dimensionality cuprates (Bi_2CuO_4 ; superconducting $La_{2-x}Sr_xCuO_4$; pure and doped spin-Peierls $CuGeO_3$; copper chain systems such as $SrCuO_2$, Sr_2CuO_3, $BaCu_2Si_2O_7$; pure and doped spin-ladder $Sr_{14}Cu_{24}O_{41}$), nickelate La_2NiO_4, cobaltates La_2CuO_4 and $LaCoO_3$, CMR manganites (pure and substituted $La_{1-x}Sr_xMnO_3$, $(La,Sr)_3Mn_2O_7$) and geometrically frustrated magnetic compounds of pyrochlore structure such as $Yb_2Ti_2O_7$ or $Gd_2Ti_2O_7$.

Examples of crystal growth conditions (growth rate, atmospheres, oxygen partial pressure…) will be given for some of these compounds and data from neutron diffraction experiments, carried out to assess crystalline perfection will be presented.

Possible segregation of dopants during growth of some of the above compounds as well as oxygen non-stoichiometry will be discussed; influence of this segregation and of oxygen non-stoichiometry on the modification of physical properties will be analyzed.

Skyrmions in chiral magnets

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In chiral magnets magnetic whirls, so-called skyrmions, can be stabilized in bulk materials in thin films. They can be manipulated by ultrasmall forces and couple efficiently to electrical-, heat- and spincurrents. The coupling arises mainly by Berry-phase effects which can be efficiently described by emergent electromagnetic fields. The talk focusses on the dynamics of skyrmions and their coupling to electrons, magnons and defects.

Quantum typicality: A novel numerical approach to dynamics and thermalization

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The concept of typicality states that a single pure state can have the same properties as the full statistical ensemble. This concept is not restricted to specific states and applies to the overwhelming majority of all possible states, drawn at random from a high-dimensional Hilbert space. In the cleanest realization, even a single eigenstate of the Hamiltonian may feature the properties of the full equilibrium density matrix, assumed in the well-known eigenstate thermalization hypothesis. The notion of property is manifold in this context and also refers to the expectation values of observables. Remarkably, typicality is not only a static concept and includes the dynamics of expectation values. Recently, it has become clear that typicality even provides the basis for powerful numerical approaches to the dynamics [1] and thermalization [2] of quantum many-particle systems at nonzero temperatures. These approaches are in the center of my talk.

In my talk, I demonstrate that typicality allows for significant progress in the study of real-time spin and energy dynamics of low-dimensional quantum magnets. To this end, I present a numerical analysis of current autocorrelation fuctions of the integrable XXZ spin-1/2 chain [1] and nonintegrable modifications with staggered magnetic fields [3] and inter-chain couplings [4]. This analysis includes a comprehensive comparison with state-of-the-art methods, including exact and Lanczos diagonalization, time-dependent density-matrix renormalization group, and perturbation theory. This comparison unveils that typicality is satisfied in finite systems over a wide range of temperature and is fulfilled in both, integrable and nonintegrable systems. For the integrable case, I calculate the long-time dynamics of the spin current and extract the spin Drude weight for large systems outside the range of exact diagonalization. I particularly provide strong evidence that the high-temperature Drude weight vanishes at the isotropic point. For the nonintegrable cases, I obtain the full relaxation curve of the energy current and determine the heat conductivity as a function of model parameters and temperature.

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Spin singlet order in breathing pyrochlore

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Pyrochlore antiferromagnets are a typical example of frustrated magnets in three dimensions. I studied the S=1/2 Heisenberg model on the pyrochlore lattice and found a dimer/tetramer order with a hierarchical structure [1]. I used an approach that the spin exchange J’ connecting tetrahedron building blocks varies from the intra-block coupling J and the ratio J’/J is a “small” control parameter in my theory. Recently, Okamoto et al. reported a material with this exchange pattern realized, and that is the S=3/2 antiferromagnet Li(Ga,In)Cr4O8 named breathing pyrochlores [2]. In the end member LiInCr4O8, the ratio J’/J is small and a magnetic order appears with lowering temperature preceded by an unidentified structure transition. I have generalized my previous theory and applied for the S=3/2 case, and discuss this transition.

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Fractional Spinonic Excitations in a 1D Quantum Antiferromagnet $SrCo_2V_2O_8$

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For quasi-one-dimensional quantum spin systems theory predicts the occurrence of a confinement of spinon excitations due to interchain couplings. Here we investigate the system $SrCo_2V_2O_8$, a realization of the weakly coupled Ising-like XXZ antiferromagnetic chains (Figure 1), by terahertz spectroscopy with and without applied magnetic field up to 30T. At low temperatures a series of excitations is observed, which split in a Zeeman-like fashion in an applied magnetic field. These magnetic excitations are identified as the theoretically predicted spinon-pair excitations. Using a one-dimensional Schrödinger equation with a linear confinement potential imposed by weak interchain couplings, the hierarchy of the confined spinons can be fully described.[1] By applying transverse magnetic fields, the spinons can be deconfined at the field-induced quantum phase transition. In the field-induced spin-liquid phase, low-energy spinonic excitations are observed with characteristic field dependencies, which are in agreement with theoretical results of the 1D XXZ antiferromagnetic model.[2]

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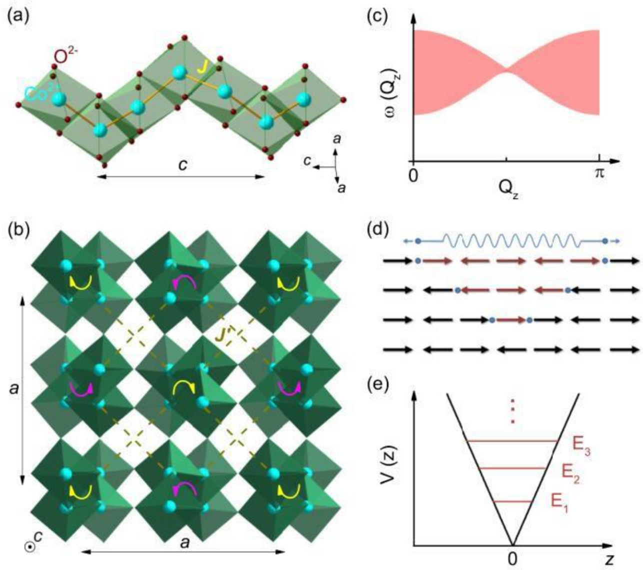

Figure 1 **|** Spinon confinement in 1D quantum antiferromagnet $SrCo_2V_2O_8$. (a) Screw chain consisting of CoO_6 octahedra running along the crystalline *c* axis in $SrCo_2V_2O_8$. (b) Projection of left- and right-handed screw chains in the tetragonal *ab* plane. The interchain exchange interaction is dominated by the antiferromagnetic interaction *J'* between the nearest-neighbor Co ions in the *ab* plane, which are from the neighboring chains with the same chirality. (c) The shaded area indicates the excitation continuum of the spinon-pair quasiparticles corresponding to the Ising-like XXZ antiferromagnetic model. The spinon pairs follow a quadratic dispersion relation along the chain direction close to the reciprocal Γ point ($Q_z = 0$). (d) Magnetic excitations of spinon pairs with total pseudospin S = 1 corresponding to an odd number of pseudospin-1/2 flips. The collinear antiferromagnetic order along the *c* axis is stabilized below 5 K. (e) Quantized spinon-pair excitation levels due to linear confinement imposed by interchain exchange interaction.[1]

Spin dynamics in triangular-lattice antiferromagnets: high-field ESR studies

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Spin-1/2 Heisenberg antiferromagnet (AF) on a triangular lattice is the paradigmatic model in quantum magnetism, which was intensively studied since several decades. In spite of numerous studies (which predict a rich variety of grounds states, ranging from a gapless spin liquid to Néel order), many important details of the phase diagram of triangular-lattice AFs remain controversial or even missing. To test the theory experimentally, a precise information on the spin-Hamiltonian parameters for the materials of interest is highly demanded. Here, we present results of high-field electron spin resonance (ESR) studies of spin-1/2 Heisenberg AF Cs_2CuCl_4 and Cs_2CuBr_4 with distorted triangular-lattice structures below and above the fully spin polarized magnetically saturated phase. In the magnetically saturated phase ($H>H_{sat}$), quantum fluctuations are fully suppressed, and the spin dynamics is defined by ordinary spin waves (magnons). This allows us to accurately describe the magnetic excitation spectra in both materials and, using the harmonic spin-wave theory, to determine their exchange parameters. The viability of the proposed method was first proven by applying it to Cs_2CuCl_4, revealing good agreement with inelastic neutron-scattering results. For the isostructural Cs_2CuBr_4 we obtain J/k_B=14.9 K, J'/k_B=6.1 K, [J'/J~0.41], providing exact and conclusive information on the exchange coupling parameters in this frustrated spin system. The approach has a broader impact and can be potentially used for *any* quantum magnet with reduced (e.g., by the staggered Dzyaloshinskii-Moriya interaction) translational symmetry, resulting, as predicted, in emergence of a new exchange mode above H_{sat}. In addition, we show that the presence of a substantial zero-field gap, ~10 K, observed in the ESR spectrum below as well as above T_N, can be interpreted in the frame of the triangular-lattice AF model, indicating good agreement with results of spin-wave calculations. The peculiarities of the ESR spectrum will be discussed taking into account the effect of staggered Dzyaloshinskii-Moriya interactions and two-magnon decay processes.

4. POSTER TITLES

Manuel Hälg: "Finite-Temperature Scaling of Spin Correlations in 1D Quantum Magnets"

Pablo Serna Martinez: “Emergent SO(5) symmetry at the Néel to Valence-Bond-Solid transition”

Patrick Navez: Large coordination number expansion for any quantum lattice system

Alessandro Nicolaou: "Fermi surface symmetry and evolution of the electronic structure across the paramagnetic-helimagnetic transition in MnSi/Si(111)"

Kirill Povarov: “Dynamics of bond-disordered DTN”

Simon Scharffe: “Specific Heat and Heat Transport of Spin-Ice Materials”

Jiang-Min Zhang: “Nonsmooth and level-resolved dynamics in a tight-binding model”