SFB/TRANSREGIO 49

FRANKFURT-KAISERSLAUTERN-MAINZ

CONDENSED MATTER SYSTEMS WITH VARIABLE MANY-BODY INTERACTIONS

INTERNATIONAL SCHOOL 2018

LINEAR RESPONSE AND NONEQUILIBRIUM DYNAMICS OF QUANTUM MANY-BODY SYSTEMS

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB/TR 185

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COLLEGES FOR THE ADVANCEMENT OF POSTGRADUATE EDUCATION

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Introduction

International School on Linear Response and Nonequilibrium Dynamics of Quantum Many-Body Systems

sponsored by

Collaborative Research Centers TR49/TR185

The International School will provide a concise overview about recent progress in the dynamics of condensed matter physics and how they can be realized in artificial systems. The pedagogical talks are provided by both experimental and theoretical physicists of international reputation.

Within the framework of the Collaborative Research Center TR49 **Condensed Matter Systems with Variable Many-Body Interactions**, which is funded since 2007 by the German Research Foundation (DFG), the collective behavior of interacting many-body systems is investigated on a broad phenomenological context. The topics embrace cooperative phenomena such as the Mott metal-insulator transition, superconducting/superfluid phases with strong interactions or Bose-Einstein condensation under various and sometimes extreme conditions. Besides the properties of the ground state, excitations and exchange processes, also containing dynamical aspects of correlations and coherence, are investigated.

The Collaborative Research Center TR185 **Open System Control of Atomic and Photonic Matter (OSCAR)** is funded since 2016 by the DFG. It explores open quantum many-body systems, where the physics results from external time-dependent drive and coupling to tailored reservoirs, in a comprehensive way across different experimental platforms. The physical realizations of choice are atoms and photons for which the technology of coherent manipulation and detection are most advanced and the miscroscopic control and understanding of both system and environment is possible.

Further information about the Collaborative Research Centers TR49/185 is available at their respective homepages

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Colleges for the Advancement of Postgraduate Education in SFB/TR49 and SFB/TR185

The researchers of the SFB/TR49 and the SFB/TR185 strive for two principle goals: The production of international first-class research results and the education of qualified experts and scientists of many-body interactions in condensed matter physics, both of which are equally important responsibilities towards society. It is an universally accepted truth that these two areas, research and postgraduate education, go hand in hand. Success in one area also requires excellence in the other and vice versa.

The Colleges for the Advancement of Postgraduate Education are integrated graduate schools with the primary intention of improving and furthering the education of young researchers affiliated with the research projects of the Transregios. The Colleges keep high academic standards and strive for an optimal graduation time of three years for PhD candidates. To this end, the Colleges provide training opportunities, guidance, and a pleasant networking environment in order to assist the research progress of doctoral students towards graduation without delays. The Colleges assist members in acquiring a variety of other skills that are expected from doctoral candidates on their way to become a self-reliant researcher, who not only excels in science, but is also ready to fill the position of a leading, responsible and independent scientist as demanded in all parts of society. The Colleges offer many customized and transregional training opportunities, such as workshops, seminars, soft skill courses, lecture series, exchanges, books, excursions, information services, and - last but not least - personal career development and guidance.

International School on Linear Response and Nonequilibrium Dynamics of Quantum Many-Body Systems

Building on the success of various educational activities within the Colleges for the Advancement of Postgraduate Studies of the SFB/TR49 and the SFB/TR185, we organize an International School which is geared towards specific topics in methods and research for students. The International School is open for international registration and the lectures will be given by invited experts. It covers many research fields of both the SFB/TR49 and the SFB/TR185 and is, therefore, of central importance.

The International School at Castle Burgbrohl covers linear response and nonequilibrium phenomena, which occur in either real or synthetic systems. In particular, concrete examples within the realm of condensed matter physics, ultracold quantum gases in traps or optical lattices, as well as ion traps are treated in detail. Although all these systems are physically quite different, their respective dynamic phenomena reveal certain similarities which will be worked out. Furthermore, the International School aims at providing an overview over both the theoretical and the experimental probing of the respective dynamic properties.

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WLAN

consult the reception

Program

International School on
Linear Response and
Nonequilibrium Dynamics of
Quantum Many-Body Systems
Castle Burgbrohl
August 13-16, 2018

SFB/TR 185

Monday, August 13

Until 10:00	Arrival
10:00-11:00	*Coffee and Registration*
11:00-11:15	Sebastian Eggert (Kaiserslautern): *Opening*
11:15-12:15	Masahito Ueda (Tokyo): *Linear response and sum rules of ultracold atomic gases – Part I*
12:15-12:30	Discussion
12:30-14.00	*Lunch*
14:00-15:00	Oliver Stockert (Dresden): *Neutron scattering: A unique microscopic probe* *to study magnetism – Part I*
15:00-15:15	Discussion
15:15-15.45	*Coffee Break*
15:45-16:45	Ulrich Schollwöck (Munich): *Time-dependence with matrix product states*
16:45-17:00	Discussion
17:00-18:00	Ulrich Schneider (Cambridge): *Quantum quenches, transport properties and thermalization* *in optical lattices*
18:00-18:15	Discussion
18:30-20:00	*Dinner*
20:00-21.30	Poster Session I

International School on
Linear Response and
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Tuesday, August 14

08:00-09:00	*Breakfast*
09:00-10:00	Ulrich Schollwöck (Munich):
	Spectral functions: Dynamical Mean-Field Theory as a challenge
10:00-10:15	Discussion
10:15-10:45	*Coffee Break*
10:45-11:45	Ulrich Schneider (Cambridge):
	Many-body localization in optical lattices
11:45-12:00	Discussion
12:15-13.45	*Lunch*
14:00-15:00	Thomas Gasenzer (Heidelberg):
	Universal dynamics near non-thermal fixed points – Part I
15:00-15:15	Discussion
15:15-15:45	*Coffee Break*
15:45-16:45	Masahito Ueda (Tokyo):
	Linear response and sum rules of ultracold atomic gases – Part II
16:45-17:00	Discussion
17:00-18:00	Oliver Stockert (Dresden):
	Neutron scattering: A unique microscopic probe
	to study magnetism – Part II
18:00-18:15	Discussion
18:30-20:00	*Dinner*
20:00-	Socializing

International School on
Linear Response and
Nonequilibrium Dynamics of
Quantum Many-Body Systems
Castle Burgbrohl
August 13-16, 2018

Wednesday, August 15

07:30-08:30	*Breakfast*
08:30-09:30	Thomas Gasenzer (Heidelberg):
	Universal dynamics near non-thermal fixed points – Part II
09:30-09:45	Discussion
09:45-10:15	*Coffee Break*
10:15-11:15	Kilian Singer (Kassel):
	The single ion heat engine – a sensitive quantum probe for non-classical baths
11:15-11:30	Discussion
11:30-13.00	*Lunch*
13:00-18:00	Excursion
	Visit of volcano museum in Mendig
18:30-20:00	*Dinner*
20:00-21.30	Poster Session II

Thursday, August 16

08:00-09:00	*Breakfast*
09:00-10:00	Michael Bauer (Kiel):
	Principles of time- and angle-resolved photoelectron spectroscopy
10:00-10:15	Discussion
10:15-10:45	*Coffee Break*
10:45-11:45	Michael Bauer (Kiel):
	Non-equilibrium carrier dynamics in two-dimensional materials
11:45-12:00	Discussion
12:15-13:45	*Lunch*
13:45-	Departure

Abstracts of Lectures

Principles of time- and angle-resolved photoelectron spectroscopy

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Time- and angle-resolved photoelectron spectroscopy (trARPES) is the potentially most direct and comprehensive, energy- and momentum-selective probe of ultrafast processes in solids that couple to the electronic degrees of freedom. Angular resolution enables one in this context to monitor the temporal evolution of the valence electronic band structure of a solid at selected - and possibly critical - points in momentum space. The lecture will give an introduction into the main principles of the trARPES technique. A particular focus will be set on challenges in the implementation of different operation schemes. The capabilities of the technique will be illustrated by different examples addressing ultrafast processes in correlated materials.

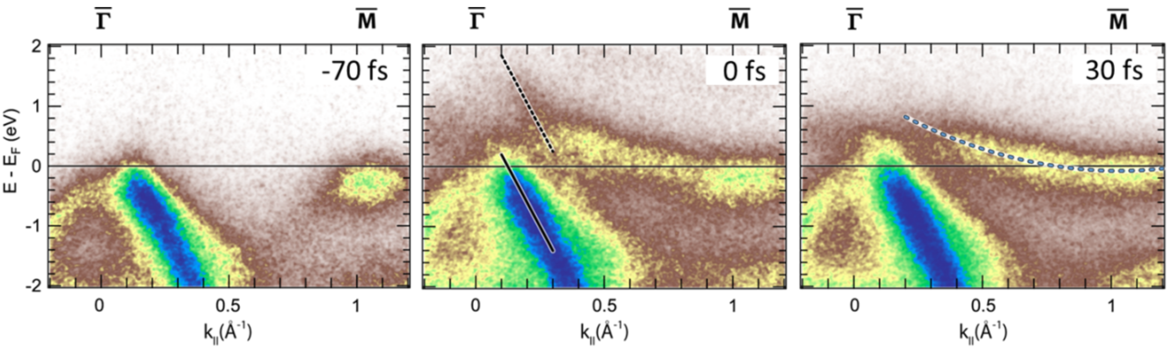

Figure 1: Photo-induced melting of a charge-ordered state in 1T-$TiSe_2$ probed by time-resolved ARPES. (Figure taken from [1].)

[1] T. Rohwer, S. Hellmann, M. Wiesenmayer, C. Sohrt, A. Stange, B. Slomski, A. Carr, Y. Liu, L.M. Avila, M. Kalläne, S. Mathias, L. Kipp, K. Rossnagel, and M. Bauer, *Collapse of long-range charge order tracked by time-resolved photoemission at high momenta*, Nature **471**, 490 (2011)

Non-equilibrium carrier dynamics in two-dimensional materials

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Studying the thermalization dynamics of non-equilibrium carrier distributions in solids allows valuable insights into the interaction processes that couple electronic, phononic and spin degrees of freedom. This lecture will introduce into relevant aspects of carrier relaxation and thermalization in two-dimensional materials. Theoretical results will be discussed and compared with experimental findings.

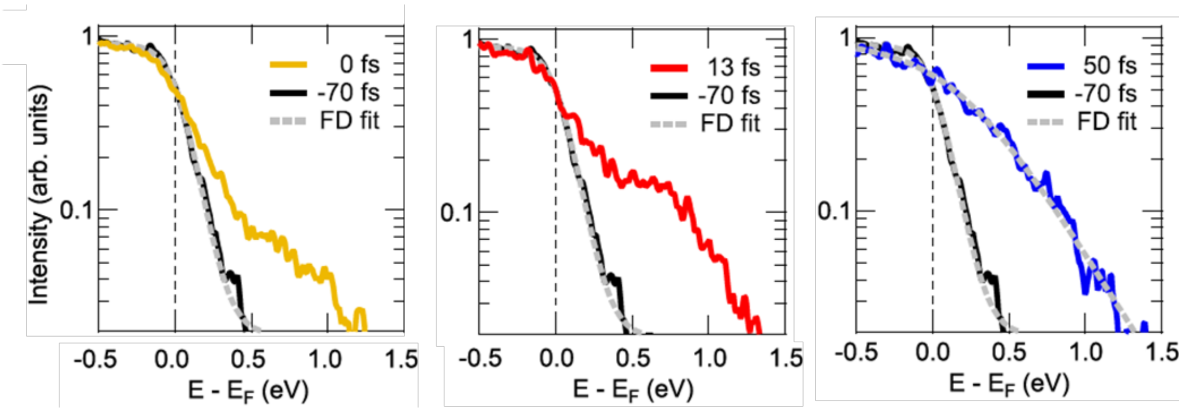

Figure 1: Formation of a Fermi-Dirac distributed electron gas in graphite within 50 fs following the excitation with a 7 fs near-infrared laser pulse. (Figure taken from [1].)

[1] G. Rohde, A. Stange, A. Müller, M. Behrendt, L.-P. Oloff, K. Hanff, T. Albert, P. Hein, K. Rossnagel, and M. Bauer, *Decoding the ultrafast formation of a Fermi-Dirac distributed electron gas*, eprint `arXiv:1804.01403`

Universal dynamics near non-thermal fixed points

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Quantum many-body systems far from equilibrium show much richer characteristics than those in equilibrium. It remains, though, an unresolved question to date how in general quantum systems with many degrees of freedom can relax and approach final equilibrium states [1,2]. Symmetries give rise to the possibility for universal dynamics, showing up with the same properties in very different systems irrespective of their concrete building blocks and allowing a classification independent of the details of microscopic properties and initial conditions. Various manifestations of such scaling dynamics are being discussed for classical systems, among them turbulence, coarsening, and phase-ordering kinetics. Non-thermal fixed points have been proposed on the grounds of the Schwinger-Keldysh approach to non-equilibrium quantum field theory. These lead beyond standard equilibrium universality and are characterized by different anomalous scaling dimensions for statistical and spectral correlation functions [3]. In my lecture, I will give an introduction to predictions for non-thermal fixed points obtained from non-equilibrium quantum field theory and discuss various manifestations in ultracold and relativistic Bose systems within and beyond present-day analytical reach.

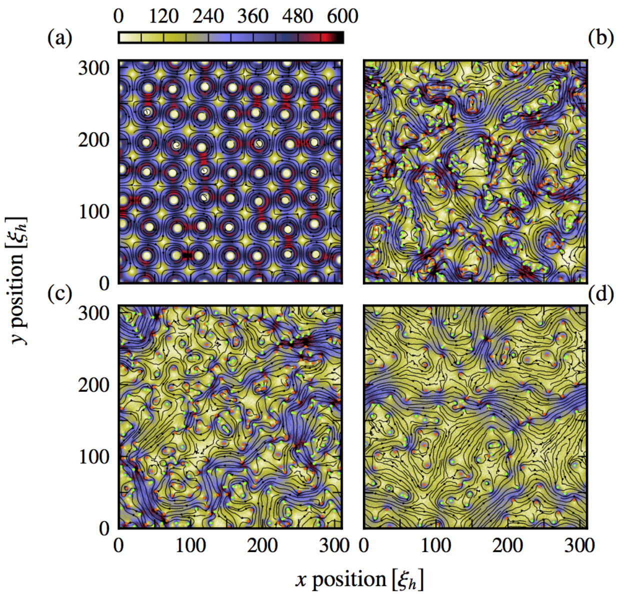

Figure 1: Strongly anomalous turbulent dynamics in the vicinity of a non-thermal fixed point in a two-dimensional superfluid Bose gas [4]. The flow pattern evolves from a far-from-equilibrium initial state containing unstable multiply charged vortices to a configuration reminiscent of classical fluid turbulence.

[1] T. Langen, T. Gasenzer, and J. Schmiedmayer, JSTAT 064009, 2016; `arXiv:1603.09385`.

[2] B. Nowak, S. Erne, M. Karl, J. Schole, D. Sexty, and T. Gasenzer, `arXiv:1302.1448`, in *Strongly Interacting Quantum Systems out of Equilibrium*, edited by T. Giamarchi, et al. (Oxford University Press, 2016).

[3] I. Chantesana, A. Pineiro Orioli, T. Gasenzer, `arXiv:1801.09490`.

[4] M. Karl and T. Gasenzer, New J. Phys. **19** 093014, 2017; `arXiv:1611.01163`.

Quantum quenches, transport properties and thermalization in optical lattices

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In this first lecture I will start with a very brief review of optical lattices and then discuss several examples of quantum quenches and how we use them to characterize transport far away from the linear response regime. I will also discuss questions of quantum thermalization in these isolated quantum systems.

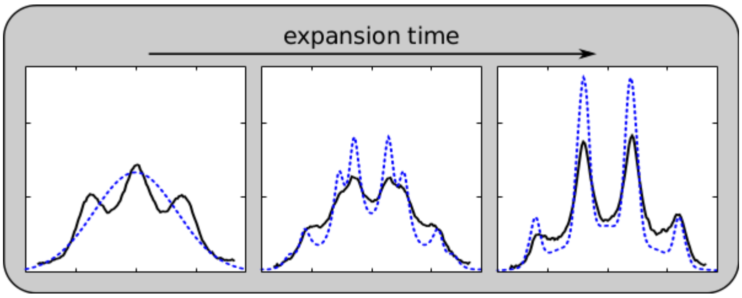

Figure 1: Evolving momentum distribution of hard-core bosons during sudden expansion.

Many-body localization in optical lattices

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Building on the material from the first lecture, we will here discuss disordered and quasi-periodic lattices in more detail and in particular focus on many-body localization, where generic, interacting many-body systems can fail to thermalize and hence can remain far-from-equilibrium for indefinite times.

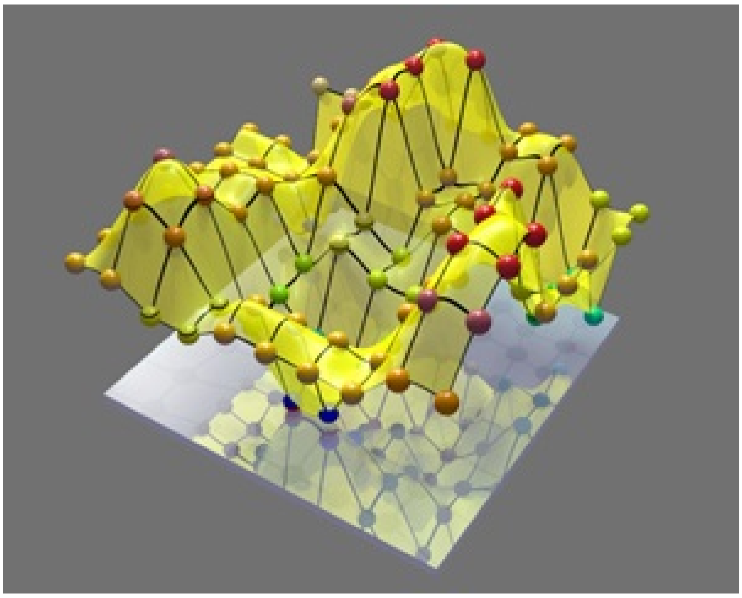

Figure 1: Disordered potential landscape giving rise to many-body localization.

Time-dependence with matrix product states

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schollwoeck@lmu.de

In this talk, I will give an introduction to methods of calculating the time-evolution of strongly correlated quantum systems in low dimensions using matrix product state methods, both at zero and finite temperature. The methods will be exemplified by applications from the non-equilibrium dynamics of ultracold gases in optical lattices and (for linear response) by applications in neutron scattering.

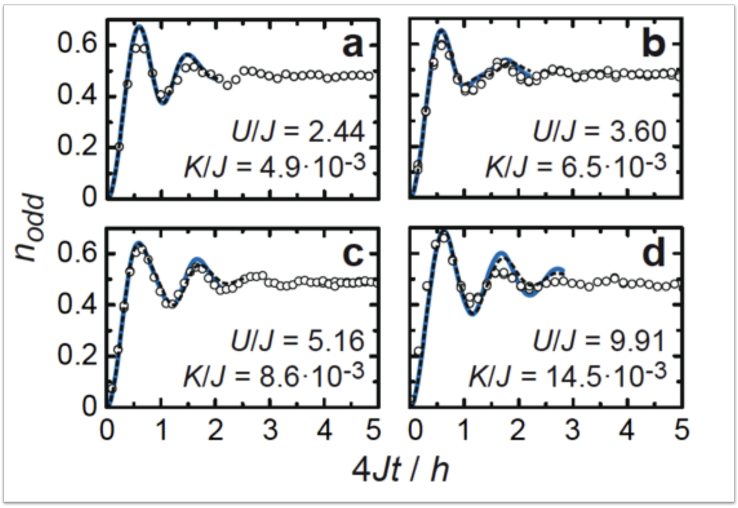

Figure 1: Relaxation of local density for different interaction strengths in a closed quantum system of ultracold atoms: simulation versus experiment [1].

[1] S. Trotzky, Y-A. Chen, A. Flesch, I.P. McCulloch, U. Schollwöck, J. Eisert, and I. Bloch, *Probing the relaxation towards equilibrium in an isolated strongly correlated one-dimensional Bose gas*, Nature Phys. **8**, 325 (2012).

Spectral functions: Dynamical Mean-Field Theory as a challenge

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In this talk, I will focus on the (potential) marriage between dynamical mean-field theory in its more advanced incarnations (multiband, dynamical cluster approximation, non-equilibrium DMFT) and matrix-product state based methods for the inevitable impurity solver which is needed to provide equilibrium and non-equilibrium Greens functions. I will highlight the pros and cons of this approach and show that a key ingredient for success is a careful rethinking of the conceptual foundations of matrix product states.

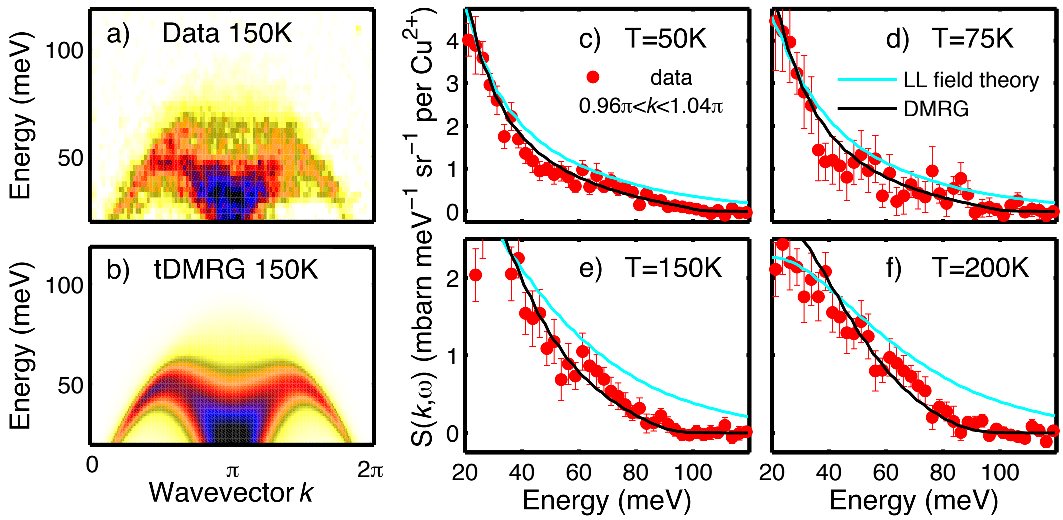

Figure 1: Spectral function from neutron scattering at spin chains: experiment versus DMRG.

The single ion heat engine - a sensitive quantum probe for non-classical baths

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Thermodynamic machines can be reduced to the ultimate atomic limit [1], using a single ion as a working agent. The confinement in a linear Paul trap with tapered geometry allows for coupling axial and radial modes of oscillation. The heat-engine is driven thermally by coupling it alternately to hot and cold reservoirs, using the output power of the engine to drive a harmonic oscillation [2]. From direct measurements of the ion dynamics, the thermodynamic cycles for various temperature differences of the reservoirs can be determined [3] and the efficiency compared with analytical estimates. I will describe how the engine principle can be exploited to implement a differential probe for non-classical baths. Furthermore I will speak about the observation of the KibbleZurek scaling law for defect formation in ion crystals [4] and how this effect could be exploited for the heat engine.

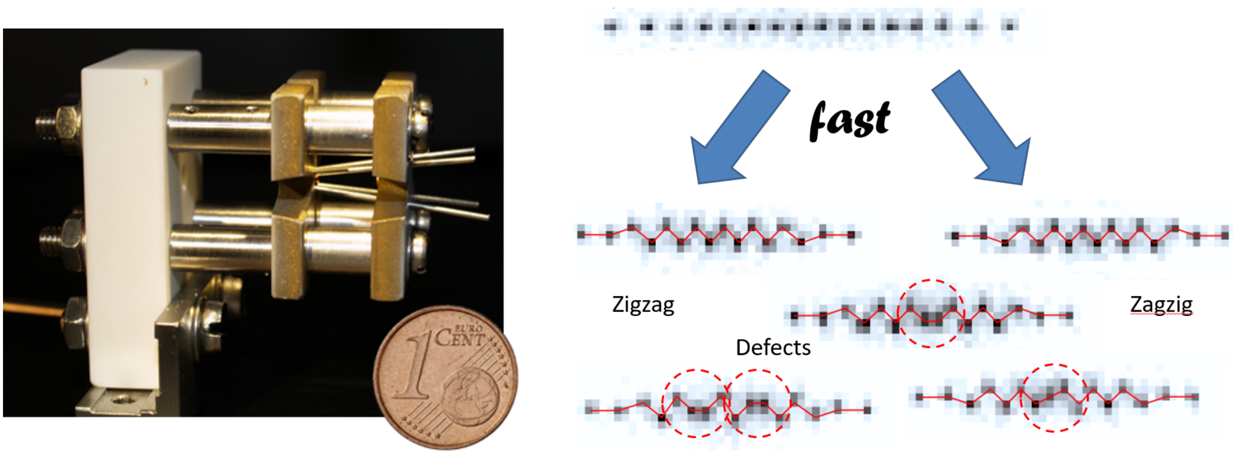

Figure 1: Left: Linear Paul trap. Right: Defect formation in ion crystals.

[1] J. Roßnagel, S.T. Dawkins, K.N. Tolazzi, O. Abah, E. Lutz, F. Schmidt-Kaler, and K. Singer, *A single-atom heat engine*, Science **352**, 325 (2016).

[2] O. Abah, J. Roßnagel, G. Jacob, S. Deffner, F. Schmidt-Kaler, K. Singer, and E. Lutz, *Single-Ion Heat Engine at Maximum Power*, Phys. Rev. Lett. **109**, 203006 (2012).

[3] J. Roßnagel, K.N Tolazzi, F. Schmidt-Kaler, and K. Singer, *Fast thermometry for trapped ions using dark resonances*, New J. Phys. **17**, 045004 (2015).

[4] S. Ulm, J. Roßnagel, G. Jacob, C. Degünther, S.T. Dawkins, U.G. Poschinger, R. Nigmatullin, A. Retzker, M.B. Plenio, F. Schmidt-Kaler, and K. Singer, *Observation of the KibbleZurek scaling law for defect formation in ion crystals*, Nature Comm. **4**, 2290 (2013).

Neutron scattering: A unique microscopic probe to study magnetism

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1) Basic Principles and Methods
The fundamental properties of the neutron are briefly introduced and the basic concepts of neutron scattering as an energy- and momentum-dependent probe to study solids are mentioned. Focusing mainly on the magnetic interaction of neutrons with unpaired electrons the cross section for magnetic neutron scattering is presented and its characteristics are discussed. The main material-dependent factor in the cross section, the spin correlation function, makes magnetic neutron scattering a unique microscopic tool to study the static and dynamic magnetic properties of matter on an atomic scale. Here, the spin correlation function is related to the generalized susceptibility using linear-response theory. Simple examples concerning magnetic neutron diffraction and inelastic scattering are presented: paramagnetism, ferromagnetism and commensurate antiferromagnetism as well as magnetic excitations including spin waves.

2) Magnetic Order and (Critical) Spin Dynamics in Strongly Correlated Electron Systems
Strongly correlated electron systems, mostly rare-earth based intermetallic compound, display a rich variety of different ground states, such as magnetically ordered, paramagnetic or superconducting. Since their ground state can be tuned by e.g. pressure, composition or magnetic field, even a $T = 0$ magnetic instability, a quantum critical point, with exciting new properties can be reached. Elastic and inelastic neutron scattering can help to identify the magnetic order, the quantum critical spin fluctuations in these systems and can give new information on the unconventional superconductivity occurring in some of the compounds. The capabilities of neutron scattering for such studies will be given.

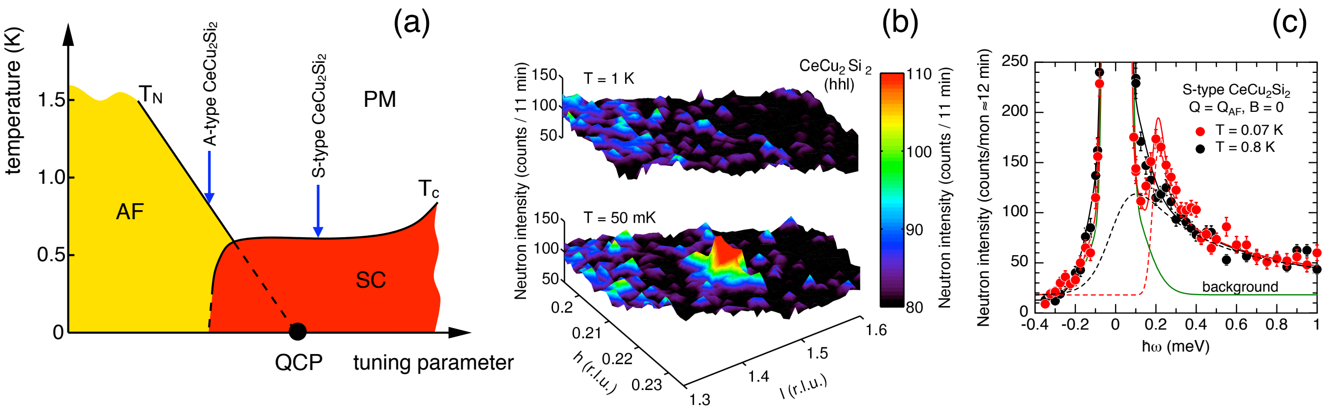

Figure 1: (a) Schematic phase diagram of a quantum critical point (QCP) showing the vicinity of $CeCu_2Si_2$ to quantum criticality with the appearance of unconventional superconductivity around the magnetic instability. (b) Intensity map of reciprocal space across the position of an antiferromagnetic superstructure peak in A-type $CeCu_2Si_2$. (c) Magnetic response in the superconducting state (at $T = 0.07\,K$) and the normal state (at $T = 0.8\,K$) of $CeCu_2Si_2$ indicating a spin excitation gap in the superconducting state (after [1, 2]).

[1] O. Stockert, E. Faulhaber, G. Zwicknagl, N. Stüßer, H. S. Jeevan, M. Deppe, R. Borth, R. Küchler, M. Loewenhaupt, C. Geibel, and F. Steglich, Phys. Rev. Lett. **92**, 136401 (2004).

[2] O. Stockert, J. Arndt, E. Faulhaber, C. Geibel, H. S. Jeevan, S. Kirchner, M. Loewenhaupt, K. Schmalzl, W. Schmidt, Q. Si, and F. Steglich, Nat. Phys. **7**, 119 (2011).

Linear response and sum rules of ultracold atomic gases

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Linear response theory provides a general theoretical framework to investigate collective modes of Bose-Einstein condensates and superfluids. A sum-rule approach is also very useful for this purpose because the ground state for a dilute-gas Bose-Einstein condensate can be obtained very accurately. Superfluidity manifests itself as a response of the system to its moving container. A statistical mechanical theory to address such problems and some basic properties of superfluidity are discussed. All of these properties are investigated by using time-ordered response functions. We will also discuss out-of-time-ordered correlations functions which have attracted considerable interest in recent years due to their relevance to nonlinear response and quantum chaos.

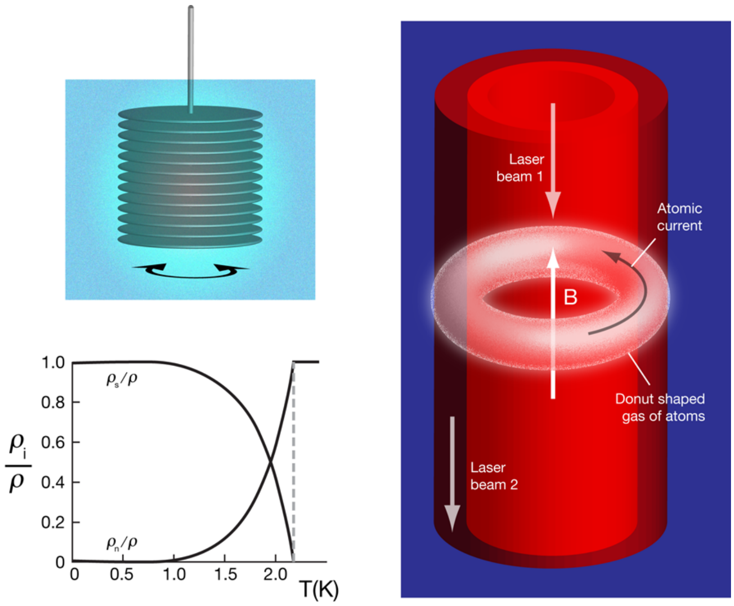

Figure 1: (Left) In 1946, Andronikashvili carried out a classic experiment on superfluid liquid helium by measuring the period and damping rate of a torsional oscillator consisting of a stack of closely spaced cylindrical plates hanging by an elastic thread and immersed in the liquid helium. The normal component of the fluid was dragged along by the rotating disk surfaces, while the superfluid took no part in the rotational motion, which allowed measurement of the fraction of the superfluid component as a function of temperature (bottom panel). (Right) Cooper and Hadzibabic [1] propose an optical method to measure the superfluid fraction in ultracold atomic gases. The pair of copropagating laser beams with different orbital angular momenta create an azimuthal vector potential that imparts angular momentum to the normal component but leaves the superfluid one at rest. Spectroscopic analysis permits measurement of the induced angular momentum and hence the amount of normal versus superfluid gas. (Figure taken from [2].)

[1] N.R. Cooper and Z. Hadzibabic, *Measuring the Superfluid Fraction of an Ultracold Atomic Gas*, Phys. Rev. Lett. **104**, 030401 (2010)

[2] I. Carusotto, *Viewpoint: Sorting superfluidity from Bose-Einstein condensation in atomic gases*, Physics **3**, 5 (2010)

List of Posters

Daniel Adam, Jennifer Koch and Jens Nettersheim (Kaiserslautern)
Controlling Spin Exchange of Single Impurities in a BEC

Javed Akram (Islamabad, Pakistan)
Bose-Einstein condensate in harmonic plus disorder potential: A search for Bose-Glass phase

Mathieu Barbier (Frankfurt)
Decay-dephasing-induced steady states in bosonic Rydberg-excited quantum gases in an optical lattice

Johannes Bauer (Kaiserslautern)
Non-equilibrium dynamics of interacting bosons in an optical lattice

Jan Lennart Bönsel (Frankfurt)
Single-particle excitation spectrum of ultracold bosons in optical lattices: Exact diagonalisation versus Bosonic dynamical mean-field theory

Martin Bonkhoff (Kaiserslautern)
Phase diagram of the extended Anyon-Hubbard model at unit filling

Ralf Bürkle (Kaiserslautern)
Hysteresis in small Bose-Hubbard systems: the microscopic onset of irreversibility?

Christoph Dauer (Kaiserslautern)
Tuning of Scattering Length by Periodic Modulation

Paul Eibisch (Frankfurt)
Magnetocaloric measurements on an organic spin-dimer system at low temperatures

Pascal Frey (Kaiserslautern)
Two-dimensional transport measurements of magneto-elastic bosons

Raphael Goll (Frankfurt)
Renormalization group for Φ^4-theory with long-range interaction and the critical exponent η of the Ising model

Niclas Heinsdorf (Frankfurt)
Electronic and topological properties of graphene nanoribbons

Kevin Jägering (Kaiserslautern)
Dynamic structure factor in impurity-doped spin chains

Hamidreza Kazemi (Kaiserslautern)
Spin transfer in interacting wires, a DMRG study

Max Kiefer (Kaiserslautern)
Dissipative 1D Open Quantum Systems of Infinite Length

Johannes Kombe (Bonn)
Observation of the Higgs mode in the superfluid BCS-BEC crossover in Fermi gases

Rui Li (Kaiserslautern)
Topology transfer from interacting Bosons to free Fermions

Qiang Luo (Beijing, China)
Ground-state phase diagram of the frustrated spin-1/2 two-leg honeycomb ladder

Polina Matveeva (Kaiserslautern)
Logarithmic corrections to dynamical correlation functions of one-dimensional spin ½ chain with impurity

Christian Thurn (Frankfurt)
Hydrostatic-pressure tuning of the magnetic states in the frustrated itinerant system YFe_4Si_2

Lukas Wawer (Kaiserslautern)
Topological order in finite-temperature and driven dissipative systems

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Notes

time	Monday	time	Tuesday	time	Wednesday	time	Thursday
until 10:00	Arrival	until 09:00	Breakfast	until 08:30	Breakfast	until 09:00	Breakfast
10:00-11:00	Coffee and Registration	09:00-10:15	**Ulrich Schollwöck** *Spectral functions: Dynamical Mean-Field Theory as a challenge*	08:30-09:45	**Thomas Gasenzer** *Universal dynamics near non-thermal fixed points – Part II*	09:00-10:15	**Michael Bauer** *Principles of time- and angle-resolved photoelectron spectroscopy*
11:00-11:15	**Sebastian Eggert** *Welcome and Opening*	10:15-10:45	Coffee Break	09:45-10:15	Coffee Break	10:15-10:45	Coffee Break
11:15-12:30	**Masahito Ueda** *Linear response and sum rules of ultracold atomic gases – Part I*	10:45-12:00	**Ulrich Schneider** *Many-body localization in optical lattices*	10:15-11:30	**Kilian Singer** *The single ion heat engine - a sensitive quantum probe for non-classical baths*	10:45-12:00	**Michael Bauer** *Non-equilibrium carrier dynamics in two-dimensional materials*
12:30-14:00	Lunch	12:15-13:45	Lunch	11:30-13:00	Lunch	12:15-13:45	Lunch
14:00-15:15	**Oliver Stockert** *Neutron scattering: A unique microscopic probe to study magnetism – Part I*	14:00-15:15	**Thomas Gasenzer** *Universal dynamics near non-thermal fixed points – Part I*	13:00-18:00	**Excursion** *Visit of volcano museum in Mendig*	13:45-	Departure
15:15-15:45	Coffee Break	15:15-15:45	Coffee Break				
15:45-17:00	**Ulrich Schollwöck** *Time-dependence with matrix product states*	15:45-17:00	**Masahito Ueda** *Linear response and sum rules of ultracold atomic gases – Part II*				
17:00-18:15	**Ulrich Schneider** *Quantum quenches, transport properties and thermalization in optical lattices*	17:00-18:15	**Oliver Stockert** *Neutron scattering: A unique microscopic probe to study magnetism – Part II*				
18:30-20:00	Dinner	18:30-20:00	Dinner	18:30-20:00	Dinner		
20:00-21:30	**Poster Session I**	20:00-	Socializing	20:00-21:30	**Poster Session II**		