Nonequilibrium Phenomena in Quantum Systems

Book of abstracts

Ambrož, Krvavec, December 17th-21st 2016

Conference schedule

	Saturday, 17. 12	Sunday, 18. 12	Monday, 19. 12	Tuesday, 20. 12	Wednesday, 21. 12
$9^{00} - 9^{30}$		Registration II	D. Mihailović	C. Gianetti	A. Potočnik
$9^{30} - 10^{00}$		Opening	C. Gadermaier	F. Cilento	V. F. Nasretdinova
$10^{00} - 10^{30}$		U. Bovensiepen	J. Demšar	I. Madan	Y. Gerasimenko
$10^{30} - 11^{00}$		F. Parmigiani	Coffee break	Coffee break	Coffee break
$11^{00} - 11^{30}$		Coffee break	P. Prelovšek	A. Green	J. Ravnik
$11^{30} - 12^{00}$		T. Tohyama	M. Mierzejewski	R. Žitko	Closing
$12^{00} - 12^{30}$		S. Ishihara	F. Heidrich-Meisner	A. Ramšak	
$16^{30} - 17^{00}$		M. Rigol	M. Eckstein	L. Vidmar	
$17^{00} - 17^{30}$		P. Werner	J.H. Mentink	D. Golež	
$17^{30} - 18^{00}$		Coffee break	Coffee break	Coffee break	
$18^{00} - 18^{30}$	Registration I	T. Prosen	V.V. Kabanov	I. Vaskivskyi	
$18^{30} - 19^{00}$		M. Medenjak	T. Mertelj	M. Capone	
$20^{30} - 21^{00}$		L. Zadnik	J. Kogoj	Z. Lenarčič	
$21^{00} - 21^{30}$		I. Kukuljan		J. Mravlje	

Nonequilibrium Phenomena in Quantum System

December 17th-21st, 2016
Ambrož, Krvavec, Slovenia

Organized by
Jožef Stefan Institute, Ljubljana Slovenia

Center of Excellence on Nanoscience and Nanotechnology – Nanocenter (CENN Nanocenter), Ljubljana, Slovenia

Faculty for Mathematics and Physics, University of Ljubljana, Slovenia

European Research Council Project

Organizing commitee
prof. dr. Janez Bonča, Jožef Stefan Institute, Ljubljana Slovenia; Faculty of Mathematics and Physics, University of Ljubljana, Slovenia

doc. dr. Tomaž Mertelj, Jožef Stefan Institute, Ljubljana Slovenia

prof. dr. Dragan Mihailović, Jožef Stefan Institute, Ljubljana Slovenia

Edited by: Žiga Osolin, Jan Kogoj

Jožef Stefan Institute, Ljubljana, Slovenia
Webpage: `http://f7-4.ijs.si/`
E-mail: `janez.bonca@ijs.si`

Sunday, 18 December

Morning Session

9:45 - 10:00	**Opening remarks**
10:00 - 10:30	**U. Bovensiepen:** Non-equilibrium dynamics of complex materials
10:30 - 11:00	**F. Parmigiani:** Science driven requirements for seeded soft x-ray free electron lasers
11:00 - 11:30	**Coffee break**
11:30 - 12:00	**T. Tohyama:** Optical conductivity out of equilibrium in one-dimensional extended Hubbard model
12:00 - 12:30	**S. Ishihara:** Nonequilibrium spin and charge dynamics in low dimensional correlated systems

Afternoon Session

16:30 - 17:00	**M. Rigol:** Emergent eigenstate solution to quantum dynamics far from equilibrium
17:00 - 17:30	**P. Werner:** Composite order in alkali-doped fulleridess
17:30 - 18:00	**Coffee break**
18:00 - 18:30	**T. Prosen:** Full relaxation dynamics of a boundary driven reversible cellular automaton
18:30 - 19:00	**M. Medenjak:** Transport and locality

Evening Session

20:30 - 21:00	**L. Zadnik:** Quasilocal conservation laws in the Hirota model
21:00 - 21:30	**I. Kukuljan:** Out-of-time-ordered correlation functions for locally interacting systems

Non-equilibrium dynamics of complex materials

U. Bovensiepen

University of Duisburg-Essen, Faculty of Physics and Center for Nanointegration (Cenide), Lotharstraße 1, 47057 Duisburg, Germany

External stimuli can drive materials far out of equilibrium and provide opportunities to develop novel means to (i) analyse excitations close to thermal equilibrium and (ii) to explore non-equilibrium states with specific properties. In this talk several examples like the dissipation of excess energy in a cuprate superconductor, [1] the dynamics of a photo-induced structural transition of the In/Si(111) surface reconstruction from (8x2) to (4x1), [2] and non-uniform spindynamics driven by photo-excited spin currents [3] will be discussed.

[1] J. D. Rameau, S. Freutel, A. F. Kemper, M. A. Sentef, J. K. Freericks, I. Avigo, M. Ligges, L. Rettig, Y. Yoshida, H. Eisaki, J. Schneeloch, R. D. Zhong, Z. J. Xu, G. D. Gu, P. D. Johnson, U. Bovensiepen Nature Commun., in press (2016).

[2] T. Frigge, B. Hafke, V. Tinnemann, T. Witte, B. Krenzer, C. Streubuhr, A. Samad Syed, V. Mikšić Trontl, I. Avigo, P. Zhou, M. Ligges, D. von der Linde, U. Bovensiepen, M. Horn-von Hoegen, submitted.

[3] I. Razdolski, A. Alekhin, N. Ilin, J. P. Meyburg, V. Roddatis, D. Diesing, U. Bovensiepen, A. Melnikov, arXiv:1606.03403.

Science driven requirements for seeded soft x-ray free electron lasers

Fulvio Parmigiani

Department of Physics - Università di Trieste

International Faculty - University of Cologne

Elettra-Sincrotrone Trieste S.C.p.A.

Starting from the archetypal FERMI externally seeded FEL, recent theoretical and experimental progress has shown the possibility of producing fully coherent, variable polarization and tunable, soft-X-ray, ultra-short pulses at high repetition rate. This ultimate achievement will unlock the gate for performing X-ray-based experiments that are qualitatively different from those available at any current or planned X-ray source. Here we will review the experiments and the ideas that represent the science frontier in soft X-ray, time-resolved spectroscopy, coherent imaging and X-ray coherent optics non-equilibrium spectroscopy. These studies will lead to an understanding of fundamental dynamics, occurring on the ultrafast time and nanometer spatial scales, needed for addressing a broad range of science essential for resolving our complex and long-term energy challenges, environmentally urgent questions and demanding problems in bioscience and novel materials.

Optical conductivity out of equilibrium in one-dimensional extended Hubbard model

Takami Tohyama

Department of Applied Physics, Tokyo University of Science, Tokyo, Japan

We have introduced a numerical method to calculate time-dependent optical conductivity for pump-probe experimental setup [1]. Using a step-like and a Gaussian-like probing vector potentials, we found that the two approaches can be identified with nonequilibrium linear-response theory and one of its variants, respectively. The probe-pulse dependence in the optical conductivity out of equilibrium was found to be especially significant, suggesting that the nature of the probe pulses should be taken into account in the analysis of ultrafast THz spectroscopy measurements. Using the method, we examine two problems related to the extended 1D Hubbard model. Firstly, we quench the Coulomb interactions from charge-density wave region to singlet superconducting region and obtain a signature of pairing of electrons in the optical conductivity [2], giving an implication to recent reports on enhanced superconductivity by photoexcitations. Secondly, we examine the THz pump-probe spectroscopy for an organic Mott insulator ET-F2TCNQ and explain an enhancement of the imaginary part of dielectric constant at the absorption edge by using the extended 1D Hubbard model with long-rang interactions [3].

[1] C. Shao, T. Tohyama, H.-G. Luo, and H. Lu, Phys. Rev. B 78, 0520501 (2016).
[2] N. Bittner, T. Tohyama, and D. Manske, in preparation.
[3] H. Okamoto et al., in preparation.

Nonequilibrium spin and charge dynamics in low dimensional correlated systems

Sumio Ishihara, Atsushi Ono, and Hiroshi Hashimoto

Department of Physics, Tohoku University, Sendai 980-8578 Japan

Ultrafast photo-induced electron dynamics in strongly correlated electron systems have significantly attracted much attention, since a number of time-resolved experimental techniques and theoretical calculation methods for non-equilibrium states are rapidly developed in the last decade. In particular, a number of exotic phenomena have been observed in correlated electron systems with multi-degrees of freedom, e.g. spin, charge, orbital, lattice and so on. I will introduce recent our theoretical studies in the photo-induced transient electron dynamics in low dimensional correlated electron systems [1-6]. In particular, we focus on the following topics.

1) The transient charge dynamics in one dimensional spin-less fermion model coupled with the local quantum vibraitons are studied [4]. Optical pulse excitation melts the charge ordered state realized by the inter-site Coulomb interaction and the electron phonon interaction. It is found that the photoinduced meltings of the charge order depends on the phonon frequency. In the small phonon frequency case, the time dependence of the charge order parameter is fitted by an exponential function with the relaxation time. The characteristic photon fluence and frequency dependences of the relaxation time are well explained by the soliton picture, where the charge order domain wall motion induces the melting. The coupling with the phonon reduces the domain wall velocity and induces

the polaron effect. On the other hand, in the case of large phonon frequency, the time profile of the order parameter does not follow the exponential function. Energy transfer from the electronic system to the lattice system occurs, that is scaled by the square of the electron-phonon coupling constant.

2) The optical induced transient dynamics in spin-charge coupled system is studied [5,6]. The double exchange model under the time depdnednt external field is analyzed in which the local spins are treated as classical spins. It is found that the AC electric field does not only suppress the electron itinerancy/the bond width but also the magnetic structure. This is interepreted as a new types of the exchange interaction in the optically excited spin-charge coupled system, that is not realized in the equilibtrium states.

[1] H. Hashimoto, H. Matsueda, H. Seo, and S. Ishihara, J. Phys. Soc. Jpn. 84, 113702 (2015).

[2] H. Hashimoto, and S. Ishihara, Phys. Rev. B 93, 165133 (2016).

[3] A. Ono, H. Hashimoto and S. Ishihara, Phys. Rev. B 94, 115152 (2016).

[4] H. Hashimoto, and S. Ishihara, (in preparation). H. Hashimoto PhD Thesis in Tohoku University (2015).

[5] J. Ohara, Y. Kanamori, and S. Ishihara, Phys. Rev. B 88, 085107 (2013).

[6] A. Ono, and S. Ishihara, (in preparation).

Emergent eigenstate solution to quantum dynamics far from equilibrium

Marcos Rigol and Lev Vidmar

Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

The quantum dynamics of interacting many-body systems has become a unique venue for the realization of novel states of matter. In this talk, we will discuss how it can lead to the generation of time-evolving states that are eigenstates of emergent local Hamiltonians, not trivially related to the ones dictating the time evolution. We study geometric quenches in interacting fermionic and bosonic systems in one-dimensional lattices, and provide examples of experimentally relevant time-evolving states [1,2] that are either ground states or highly excited eigenstates of emergent local Hamiltonians [3].

[1] M. Rigol and A. Muramatsu, Phys. Rev. Lett. **93**, 230404 (2004).

[2] L. Vidmar, J.P. Ronzheimer, M. Schreiber, S. Braun, S.S. Hodgman, S. Langer, F. Heidrich-Meisner, I. Bloch, and U. Schneider, Phys. Rev. Lett. **115**, 175301 (2015).

[3] L. Vidmar, D. Iyer, and M. Rigol, arXiv:1512.05373.

Composite order in alkali-doped fullerides

P. Werner[1], H. Strand [1], S. Hoshino [2] and M. Eckstein [3]

[1] *Department of Physics, University of Fribourg, Chemin du Musée 3, 1700 Fribourg, Switzerland*

[2] *RIKEN Center for Emergent Matter Science (CEMS), Wako, Saitama 351-0198, Japan*

[2] *Max Planck Research Department for Structural Dynamics, University of Hamburg-CFEL, 22761 Hamburg, Germany*

Alkali-doped fullerides are half-filled three-orbital systems which have been extensively studied in connection with their unconventional *s*-wave superconductivity. The unique feature of this class of materials is their effectively negative Hund coupling which results from an overscreening of the small static Hund interaction by Jahn-Teller phonons [1]. Some of these materials also feature an unusual Jahn-Teller metal phase characterized by a microscopic coexistence of insulating and metallic behavior [2].

In the first part of my talk, I will present some recent theoretical insights into the origin of the unconventional superconductivity and the Jahn-Teller metal phase. The latter is shown to result from a *spontaneous* orbital-selective Mott transition. The symmetry-broken state has no ordinary order parameter, but a composite order parameter (orbital-dependent double occupation), which may be regarded as a diagonal-order version of odd-frequency superconductivity [3].

In the second part of the talk, we will consider the switching of this ordered state between different physical realizations corresponding to different anisotropies in the conductivity. We will show that the order parameter can be rotated in a controlled fashion by temporarily reducing the hopping amplitudes between different orbitals.

[1] M. Capone, M. Fabrizio, C. Castellani, and E. Tosatti, Rev. Mod. Phys. 81, 943 (2009).

[2] R. H. Zadik, Y. Takabayashi, G. Klupp, R. H. Colman, A. Y. Ganin, A. Potocnik, P. Jeglic, D. Arcon, P. Matus, K. Kamaras, Y. Kasahara, Y. Iwasa, A. N. Fitch, Y. Ohishi, G. Garbarino, K. Kato, M. J. Rosseinsky, K. Prassides, Science Advances 1, e1500059 (2015).

[3] S. Hoshino and P. Werner, arXiv:1609.00136 (2016).

Full relaxation dynamics of a boundary driven reversible cellular automaton

T. Prosen[1] , B. Buča[2]

[1] *Faculty for mathematics and physics, University of Ljubljana, Jadranska ulica 19, SI-1000 Ljubljana, Slovenia*

[2] *School of Medicine, University of Split, Šoltanska 2, HR-21000 Split, Croatia*

A simple inhomogeneous matrix ansatz will be presented, which describes the steady state, and more importantly, the decay modes — the spectrum and eigenvectors of Liouvillian — in a simple (perhaps minimal) paradigm of boundary driven non-equilibrium strongly interacting system: conservative cellular automaton driven by stochastic boundaries.

Transport and locality

M. Medenjak

Faculty for mathematics and physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia

The nature of transport is one of the central questions in the study of many-body quantum systems. The systems can exhibit wide range of transport phenomena, such as ideal, anomalous and diffusive transport, as exemplified by the paradigmatic Heisenberg XXZ model. In the presentation I will make a connection between the transport coefficients and local conservation laws and show some exact results for the Heisenberg XXZ model.

Quasilocal conservation laws in the Hirota model

L. Zadnik, T. Prosen

Faculty for mathematics and physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia

Hirota model is an integrable discretization of the Sine-Gordon model of the field theory. It corresponds to a periodically driven chain of cyclic spins. I will present the construction of quasilocal conserved charges from Faddeev-Volkov integrals of motion.

[1] L. Zadnik, T. Prosen, *in progress.*
[2] L. Faddeev, A. Yu. Volkov, *Letters in Mathematical Physics* **32** (1994) 125-135.
[3] A. Yu. Volkov, *Physics Letters A* **167** (1992) 345-355.
[4] E. Ilievski, M. Medenjak, T. Prosen, *Phys. Rev. Lett.* **115** (2015) 120601.
[5] A. Antonov, *Theor. Math. Phys.* **113** (1997) 1520-1529.
[6] V. Bazhanov, A. Bobenko, N. Reshetikhin, *Commun. Math. Phys.* **175** (1996) 377-400.

Out-of-time-ordered correlation functions for locally interacting systems

I. Kukuljan and T. Prosen

Faculty for mathematics and physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia

Motivated by a work of Larkin and Ovchinnikov on quasiclassical methods in the theory of superconductivity, the so called out-of-time-ordered correlation functions (OTOC) have recently become a hot topic of the high-energy community. They are argued to be connected to chaoticity and the speed of propagation of information in quantum many-body systems and are a conceptually new object to study these phenomena. Due to unusual time-ordering, we don't yet have good general tools for the computation of OTOCs. The high-energy community have mostly been computing them for systems with long-range interaction. An upper bound for the growth of OTOCs has been conjectured and systems saturating it found. On the other hand, the condensed-matter community have got interested in the topic, as well, and have produced a few interesting results for physically more relevant systems with local interaction. These include MBL systems. It has been shown that OTOCs can even be experimentally measured which distinguishes them from other objects quantifying quantum chaos.

In our work that is to be published, we argue that for systems with fermionic degrees of freedom, OTOCs of local operators, which are usually computed, are not a good measure of quantum chaos as these have bounded spectra. Instead, one has to look at OTOCs of extensive observables. We show that these grow to infinity for a generic system. However, for an integrable system and observables composed of terms which are quadratic in fermionic operators, OTOCs saturate to a plateau. In my talk, I will give a quick overview of the known results on OTOCs and present our work on OTOCs for locally interacting fermionic systems.

Monday, 19 December

Morning Session

9:00 - 9:30	**D. Mihailović:** Quantum ordering dynamics of topological polaron states
9:30 - 10:00	**C. Gadermaier:** Transition metal dichalcogenide 2D semiconductors: photoexcitation dynamics and unconventional Stark effect
10:00 - 10:30	**J. Demsar:** Electron-boson coupling strengths in e-doped cuprate superconductors
10:30 - 11:00	**Coffee break**
11:00 - 11:30	**P. Prelovšek:** Many-body localization in disordered Hubbard model
11:30 - 12:00	**M. Mierzejewski:** Long-lasting, yet transient subdiffusion of charge carriers in strongly disorder$t$–J model
12:00 - 12:30	**F. Heidrich-Meisner:** Nonequilibrium dynamics of interacting quantum gases in optical lattices

Afternoon Session

16:30 - 17:00	**M. Eckstein:** Electric field control of many-body exchange interactions
17:00 - 17:30	**J. H. Mentink:** Ultrafast quantum spin dynamics in Heisenberg antiferromagnets caused by optical modification of the exchange interaction
17:30 - 18:00	**Coffee break**
18:00 - 18:30	**V. V. Kabanov:** Magnetic quantum oscillations in doped antiferromagnetic insulators
18:30 - 19:00	**T. Mertelj:** Collective electronic orders under strong optical drive studied by means of time-resolved multipulse optical spectroscopy

Evening Session

20:30 - 21:00	**J. Kogoj:** Nature of Bosonic Excitations revealed by high–energy charge carriers

Quantum ordering dynamics of topological polaron states

Y.Gerasimenko, I.Vaskivskyi, D.Mihailović

Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

Polarons - quasiparticles entangling electronic and lattice degrees of freedom have motivated at least two breakthroughs in 20th century physics: conducting polymers and high-temperature superconductors. In spite of significant research, their many-body behaviour is often complex and poorly understood. They can behave as itinerant band-like quasiparticles or localized charges, and sometimes both forms coexist. Topology can play an important role in both single polaron and many body behaviour of polarons. A particularly well known example are topologically stabilized polaron states in 1D systems. In higher dimensions the existence of topologically protected polarons is not so evident. Exceptionally, in the 2D layered dichalcogenide 1T-TaS2, topologically stabilized quantum defects appear in the form of voids and other more complicated topological objects on a polaron lattice. Remarkably, these can be created or manipulated optically with short laser pulses or by the tip of an STM. At high density, and under non-equilibrium conditions, the voids self-organize into ordered domain walls, leading to the well-known hidden state in this material with coexisting itinerant and localised polarons. The long range order is driven by an underlying Fermi surface instability.

Transition metal dichalcogenide 2D semiconductors: photoexcitation dynamics and unconventional Stark effect

C. Gadermaier[1,2], T. Borzda[1,2], D. Vella[1,2], V. Vega-Mayoral[1,2], E.A.A. Pogna[4], B. Visic[5], L. Yadgarov[5], R. Tenne[5], G. Cerullo[4], D.Mihailovic[1,2,3]

[1] *Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *Jozef Stefan International Postgraduate School, Jamova 39, SI-1000 Ljubljana, Slovenia*

[3] *Center of Excellence on Nanoscience and Nanotechnology – Nanocenter (CENN Nanocenter), Jamova 39, SI-1000 Ljubljana, Slovenia*

[4] *Department of Physics, Politecnico di Milano, P. Leonardo da Vinci 32, 20133 Milano, Italy*

[5] *Department of Materials and Interfaces, Weizmann Institute of Science, Rehovot 76100, Israel*

Strong spatial confinement and strongly reduced screening in low-dimensional materials leads to important interactions between photoexcited electrons and holes. Consequently, the single-particle picture is insufficient to describe their photophysics and many-body electron interactions have to be taken into account. Here we show how to disentangle the quasiparticle and many-body contributions to the pump-probe signal of few-layer WS_2. We show that photoexcitation close to the C exciton resonance immediately leads to a derivative-like signal due to renormalization of the band gap and the exciton binding energy. Subsequently, the photoinduced absorption by charge carriers and the bleaching of the exciton resonance form on a time scale of 1 ps. Inorganic WS2 fullerenes and nanotubes of semiconducting transition metal dichalcogenides show exceptionally high free carrier density, enabling localized surface plasmon resonances in the near-infrared to visible region. The coexistence of plasmons and excitons in the WS_2 nanotubes leads to their coupling and hybridization. This makes them the first non-composite material on which such hybridization has been observed. We show the femtosecond dynamics of the exciton-plasmon coupling, which is governed both by band gap renormalization and population dynamics.

Electron-boson coupling strengths in e-doped cuprate superconductors

M. Beck[1], M. Obergfell[1,2], Y. Dagan[3], V.V. Kabanov[4], J. Demsar[1,2]

[1] *Dept. of Physics, Univ. of Konstanz, 78457 Konstanz, Germany*

[2] *Institute of Physics, Johannes Gutenberg-University Mainz, 55128 Mainz, Germany*

[3] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel*

[4] *Complex Matter Department, Jozef Stefan Institute, 1000 Ljubljana, Slovenia*

The quest for a pairing boson in cuprate high-temperature superconductors is one of the outstanding tasks of solid state physics. Numerous time-resolved studies of pair-breaking, related to pairing by the time-reversal symmetry, have been performed using femtosecond optical pulses. By considering energy relaxation pathways between charge, spin and lattice degrees of freedom, evidence for both, phonon and antiferromagnetic fluctuation mediated pairing have been obtained. Here we present the study of the superconducting state depletion process in an electron doped cuprate $P_{1.85}Ce_{0.15}CuO_{4-x}$, where the superconducting gap is smaller than the energy of relevant bosonic excitations [1]. When pumping with above-gap THz pulses, we find the absorbed energy density required to deplete superconductivity, Adep, matches the thermodynamic condensation energy. Contrary, by near-infrared pumping, Adep is an order of magnitude higher, like in the case of hole-doped, large gap, cuprates. These results imply that only a small subset of bosons, which are generated during the relaxation of optically excited carriers contribute to pairing. The observation implies that, contrary to the common assumptions, the electron-boson coupling in the cuprates strongly depends on electron energy. Considering the competing scenarios of superconductivity being mediated by the phonons or magnetic excitations, the result suggests that high energy electrons strongly couple to either phonons or magnetic modes, while the situation is reversed for the low energy electrons. Taking into account the result that near-infrared pumping in YBCO results in a rapid electron-phonon energy transfer [2], we may conclude that pairing in cuprates is mediated by magnetic excitations. Alternatively, we could assume that high energy electrons emit magnetic excitation on the fs timescale, as recently suggested [3]. If this is the case, these nonequilibrium magnetic excitations are almost uncoupled from the condensate and therefore do not act as pair-breakers.

[1] N. P. Armitage, P. Fournier, R. L. Greene, Rev. Mod. Phys. 82, 2421 (2010).

[2] A. Pashkin, et al., Phys. Rev. Lett. 105, 067001 (2010).

[3] S. Dal Conte, et al., Nature Physics 11, 421-426 (2015).

Many-body localization in disordered Hubbard model

P. Prelovšek [1,2] , O. S. Barišić [3], M. Žnidarič [2]

[1] *Jožef Stefan Institute, Ljubljana, Slovenia*

[2] *Faculty for mathematics and physics, University of Ljubljana, Ljubljana, Slovenia*

[3] *Institute of Physics, Zagreb, Croatia*

Strong disorder can induce in correlated fermionic systems the many-body localized state, which has several unusual properties, among them the nonergodic behaviour of dynamical correlation, the absense of themalization and the vanishing of d.c. transport at any finite temperature. Theoretical studies of this phenomenon have been so far restricted to models of spinless fermions, while experimental evidence comes from cold-atom systems which can be described by the disordered Hubbard model with random local potentials. It will be demonstated that the behaviour of the latter model is qualitative different from the spinless one, since in contrast to charge correlations spin degrees remain ergodic even in the presence of strong disorder.

Long-lasting, yet transient subdiffusion of charge carriers in strongly disorder t–J model

J. Bonča[1,2] , M. Mierzejewski [3]

[1] *Faculty for mathematics and physics, University of Ljubljana, Jadranska ulica 19, 1000 Ljubljana, Slovenia*

[2] *Department for theoretical physics, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*

[3] *Institute of Physics, University of Silesia, 40-007 Katowice, Poland*

We study dynamics of a single charge carrier which is coupled to spin excitations and propagates in a disordered lattice. Our studies are carried out for the one dimensional t–J model, which should be considered as a limiting case of the Hubbard model for large on-site repulsion. We demonstrate that localization of charge carriers is possible only for localized spin excitations, whereas their dynamics is subdiffusive (or diffusive for weak disorder) when spins are delocalized. We show also that the subdiffusive behavior originates from extremely broad distribution of propagation–times between the neighboring lattice sites. However, this distribution strongly suggests that the subdiffusive behavior is a transient, yet long-lasting phenomenon. The transition to the normal diffusive regime takes place at extremely long times and cannot be observed from bare numerical data.

Nonequilibrium dynamics of interacting quantum gases in optical lattices

F. Heidrich-Meisner[1]

[1] *Arnold Sommerfeld Center for Theoretical Physics, LMU Munich, Germany*

Experiments with ultracold quantum gases play a vital role in driving the field of nonequilibrium dynamics of closed quantum many-body systems. A particular focus has been on the question of thermalization and examples of systems that fail to thermalize, including one-dimensional integrable systems or many-body localization. By considering the example of the experiment by Ronzheimer et al. [1], in which both an interaction quench and the release of bosons from a trap into an empty optical lattice (sudden expansion) was realized, I discuss several nonequilibrium effects of strongly interacting quantum gases. These include the thermalization of a closed quantum system and its connection to the eigenstate thermalization hypothesis [2], nonequilibrium mass transport [1], dynamical fermionization [3], and transient phenomena such as quantum distillation or dynamical quasicondensation [4]. I will highlight the role of integrability in giving rise to ballistic transport in strongly interacting 1D systems [1] and in determining the asymptotic state after a quantum quench [5]. The talk concludes with a perspective on open questions concerning 2D systems and the numerical simulation of their nonequilibrium dynamics [6].

[1] Ronzheimer et al., Phys. Rev. Lett. 110, 205301 (2013)
[2] Sorg et al., Phys. Rev. A 90, 033606 (2014)
[3] Vidmar et al., Phys. Rev. B 88, 235117 (2013)
[4] Vidmar et al., Phys. Rev. Lett. 115, 175301 (2015)
[5] Mei et al., Phys. Rev. A 93, 021607(R) (2016)
[6] Hauschild, Pollmann, FHM, Phys. Rev. A 92, 053629 (2015)

Electric field control of many-body exchange interactions

M. Eckstein

Max-Planck Institute for the structure and Dynamics of Matter, 22761 Hamburg, Germany

In this talk I provide a theoretical view on how strong dc and ac electric fields can be used to modify effective interactions between low energy degrees of freedom, such as spin and orbital exchange interactions, or phonon mediated electron-phonon couplings. I will consider both the case of periodically oscillating fields, as well as slower varying field, such as strong few-cycle THz pulses. This is a generalisation of previous work [1] which showed that oscillating fields can modify the magnetic exchange interactions. As concrete examples, I will show that periodic fields can drive a Kondo impurity into a quantum critical regime of the two-channel Kondo effect, and the possibility to couple light to orbital ordering.

[1] J. Mentink, K. Balzer, and M. Eckstein, Nature Communications 6, 6708 (2015).

Ultrafast quantum spin dynamics in Heisenberg antiferromagnets caused by optical modification of the exchange interaction

J.H. Mentink

Radboud University, Institute for Molecules and Materials, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands

Magnetic ordering originates from the exchange interaction, the strongest interaction between microscopic spins. In thermodynamic equilibrium, this concept is well known and can often be conveniently described by the Heisenberg exchange Hamiltonian

$$H = \sum_{\langle ij \rangle} J_{ij} S_i S_j \tag{1}$$

where J_{ij} is the exchange parameter and S_i and S_j are spins at neighboring sitesi, j of a lattice. However, much less is known about the validity of this concept under electronic nonequilibrium conditions such as generated by femtosecond laser excitation. Here we present recent theoretical advances [1,2] which demonstrate an ultrafast control of exchange interactions. Interestingly, we find that depending on the laser frequency and intensity an enhancement, reduction and even complete reversal of the sign of the exchange interaction can be achieved. Moreover, we show how such ultrafast control of the exchange interaction can be used to manipulate magnetic order. Besides the excitation of classical spin precession in canted antiferromagnets that has been recently observed in experiments

[3], we demonstrate that ultrafast modification exchange interaction can excite genuine quantum spin dynamics. Opposed to the conventional one-magnon spin resonances, this comprises coherent dynamics of magnon pairs with opposite momenta. They manifest themselves in longitudinal oscillations of the antiferromagnetic order parameter as has recently been observed [4,5]. We show that these dynamics can be conveniently describes using magnon-pair operators and demonstrate that the oscillations stem from the competition between Ising and spin-flip terms of the isotropic Heisenberg spin Hamiltonian [6]. Finally, focussing on strong perturbations of the exchange interaction, which may be feasible in cold atom systems, we find that a change of sign of the exchange interaction causes an effective time-reversal of the quantum spin dynamics, which enables a new way to assess fundamental questions concerning the reversibility of the quantum many-body dynamics in cold atom systems.

[1] J.H. Mentink and M. Eckstein, Phys. Rev. Lett. 113, 057201 (2014)
[2] J.H. Mentink, K. Balzer, M. Eckstein, Nat. Commun. 6, 6708 (2015)
[3] R.V. Mikhaylovskiy et al., Nat. Commun. 6, 8190 (2015)
[4] J. Zhao et al., Phys. Rev. Lett 93, 107203 (2004)
[5] D. Bossini, et al., Nat. Commun. 7, 10645 (2016)
[6] D. Bossini et al., in preparation (2016)

Magnetic quantum oscillations in doped antiferromagnetic insulators

V. V. Kabanov

Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

Energy spectrum of electrons (holes) doped into a two-dimensional antiferromagnetic insulator is quantized in an external magnetic field of arbitrary direction. A peculiar dependence of the de Haas-van Alphen or the Shubnikov-de Haas magneto-oscillation amplitudes on the azimuthal in-plane angle from the magnetization direction and on the polar angle from the out-of-plane direction is found, which can be used as a sensitive probe of the antiferromagnetic order in the doped Mott-Hubbard, spin-density wave, and conventional band structure insulators[1]. Experiments in which the predicted angular dependence is observed are discussed.

[1] V. V. Kabanov and A. S. Alexandrov Phys. Rev. B 77, 132403 (2008)

Collective electronic orders under strong optical drive studied by means of time-resolved multipulse optical spectroscopy

A. Pogrebna[1,2], I. Madan[1], P. Kusar[1], M. Naseska[1], V. V. Kabanov[1], T. Mertelj[1,3], Z. A. Xu[4], M. Oda[5], D. Mihailovic[1,3]

[1] *Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *Radboud University, Institute for Molecules and Materials, Nijmegen 6525 AJ, The Netherlands*

[3] *Center of Excellence on Nanoscience and Nanotechnology – Nanocenter (CENN Nanocenter), Jamova 39, SI-1000 Ljubljana, Slovenia*

[4] *Department of Physics, Zhejiang University, Hangzhou 310027, People's Republic of China*

[5] *Department of Physics,Hokkaido University, Sapporo 060-0810, Japan*

Ultrafast phase transitions from and into electronically ordered states, which occur during the quench following a strong femtosecond laser excitation, have become a rather hot research topic during the last decade. Experimentally various electronic orders were investigated with emphasis on ferromagnetism[1], charge and orbital ordering[2], charge density waves[3] as well as superconductivity[4]. Despite a significant occurrence frequency of antiferromagnets the collinear antiferromagnetism and the related spin density wave (SDW) order were among the less studied orders[5] in this context, perhaps due to the absence of the linear coupling of the order parameter to photons.

Despite the lack of momentum sensitivity and in general complicated response functions all-optical time resolved spectroscopy can give some insight into ultrafast optical quenches of electronic order parameters. I will present some of our recent efforts reaching beyond the standard 2-pulse pump-probe technique applied to the cuprate superconductors and the antiferromagnetic spin density wave in undoped iron based pnictides.

[1] A. Kirilyuk, A. V. Kimel, T. Rasing, Rev. Mod. Phys. 82, 2731 (2010).

[2] T. Ogasawara, T. Kimura, T. Ishikawa, M. Kuwata-Gonokami, and Y. Tokura, Phys. Rev. B 63, 113105 (2001).

[3] P. Kusar, V. V. Kabanov, J. Demsar, T. Mertelj, S. Sugai, and D. Mihailovic, Phys. Rev. Lett. 101, 22700 (2008).

[4] F. Schmitt et al., Science 321, 1649 (2008).

[5] A. V. Kimel, R. V. Pisarev, J. Hohlfeld, and Th. Rasing, Phys. Rev. Lett. 89, 287401 (2002).

Nature of Bosonic Excitations revealed by high–energy charge carriers

J. Kogoj [1], M. Mierzejewski [2], J. Bonča[1,3]

[1] *Department for theoretical physics, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*

[2] *Institute of Physics, University of Silesia, 40-007 Katowice, Poland*

[3] *Department for theoretical physics, Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*

We address a long standing problem concerning the origin of bosonic excitations that strongly interact with charge carriers. We show that the time-resolved pump–probe experiments are capable to distinguish between regular bosonic degrees of freedom, e.g. phonons, and the hard-core bosons, e.g., magnons. The ability of phonon degrees of freedom to absorb essentially unlimited amount of energy renders relaxation dynamics nearly independent on the absorbed energy or the fluence. In contrast, the hard core effects pose limits on the density of energy stored in the bosonic subsystems resulting in a substantial dependence of the relaxation time on the fluence and/or excitation energy. Very similar effects can be observed also in a different setup when the system is driven by multiple pulses.

[1] J. Kogoj et al. Phys. Rev. Lett. 117, 227002 (2016)

Tuesday, 20 December

Morning Session

9:00 - 9:30	**C. Giannetti:** Emergent ultrafast phenomena in correlated oxides and heterostructures
9:30 - 10:00	**F. Cilento:** Combined table-top ultrafast optical and photoelectron spectroscopies shed new light on the relaxation dynamics in copper oxides
10:00 - 10:30	**I. Madan:** Observation of new types of photoinduced states: dynamical states in 1D superconductors and direct observation of photoinduced spin textures in chiral magnets
10:30 - 11:00	**Coffee break**
11:00 - 11:30	**A. G. Green:** Feynman Path Integrals and Quantum Langevin Equations Over Entangled States
11:30 - 12:00	**R. Žitko:** Universality manifesting through characteristic energy ratios of bound states in gapped impurity systems
12:00 - 12:30	**A. Ramšak:** Magic Ratios of Linear Conductances of Gated Graphene Structures

Afternoon Session

16:30 - 17:00	**L. Vidmar:** Generalized eigenstate thermalization in integrable lattice models
17:00 - 17:30	**D. Golež:** Manipulation of screening in Mott's insulators
17:30 - 18:00	**Coffee break**
18:00 - 18:30	**I. Vaskivskyi:** Interplay between different orders in 1T-TaS_2
18:30 - 19:00	**M. Capone:**

Evening Session

20:30 - 21:00	**Z. Lenarčič:** Pumping approximately integrable models
21:00 - 21:30	**J. Mravlje:** Correlated-electron transport in hcp-Fe under extreme conditions present in inner Earth Core

Emergent ultrafast phenomena in correlated oxides and heterostructures

M. Gandolfi[1,2,3], L. Celardo[1,2], F. Borgonovi[1,2], G. Ferrini[1,2], A. Avella[4,5,6], F. Banfi[1,2], C. Giannetti[1,2]

[1] *Department of Physics, Università Cattolica del Sacro Cuore, Brescia I-25121, Italy*

[2] *I-LAMP (Interdisciplinary Laboratories for Advanced Materials Physics), Università Cattolica del Sacro Cuore, Brescia I-25121, Italy*

[3] *Laboratory of Soft Matter and Biophysics, Department of Physics and Astronomy, KU Leuven, Celestijnenlaan 200D, B-3001 Heverlee, Leuven, Belgium*

[4] *Dipartimento di Fisica "E.R. Caianiello", Università degli Studi di Salerno, I-84084 Fisciano (SA), Italy*

[5] *CNR-SPIN, UoS di Salerno, Via Giovanni Paolo II 132, I-84084 Fisciano (SA), Italy*

The possibility of investigating the dynamics of solids on timescales faster than the thermalization of the internal degrees of freedom has disclosed novel non-equilibrium phenomena that have no counterpart at equilibrium. Transition metal oxides (TMOs) provide an interesting playground in which the correlations among the charges in the metal d-orbitals give rise to a wealth of intriguing electronic and thermodynamic properties involving the spin, charge, lattice and orbital orders. Furthermore, the physical properties of TMOs can be engineered at the atomic level, thus providing the platform to investigate the transport phenomena on timescales of the order of the intrinsic decoherence time of the charge excitations. Here, we review and discuss three paradigmatic examples of transient emerging properties that are expected to open new fields of research: i) the creation of non-thermal magnetic states in spin-orbit Mott insulators; ii) the possible exploitation of quantum paths for the transport and collection of charge excitations in TMO-based few-monolayers devices; iii) the transient wave-like behavior of the temperature field in strongly anisotropic TMOs.

[1] M. Gandolfi et al. arXiv:1609.07394 (2016)

Combined table-top ultrafast optical and photoelectron spectroscopies shed new light on the relaxation dynamics in copper oxides

F. Cilento[1], S. Peli[2], A. Crepaldi[1], G. Manzoni[3], A. Sterzi[3], M. Zacchigna[4], C. Cacho[5], E. Springate[5], M. [6], A. Damascelli[6], C. Giannetti[2], F. Parmigiani[1,3]

[1] *Sincrotrone Trieste S.C.p.A., Basovizza I-34012, Italy*

[2] *Department of Physics, Università Cattolica del Sacro Cuore, Brescia I-25121, Italy*

[3] *Università degli Studi di Trieste, Trieste I-34127, Italy*

[4] *CNR–IOM, Strada Statale 14, km 163.5, Trieste 34149, Italy*

[5] *Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell OX11 0QX, United Kingdom*

[6] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada; Quantum Matter Institute, University of British Columbia, Vancouver, BC V6T 1Z4, Canada*

Time-resolved optical spectroscopies revealed very powerful for addressing several long-lasting open issues in the field of copper oxides. By combining complementary spectroscopies, including optical and photoelectronic probes, a comprehensive picture about the relaxation dynamics in strongly correlated copper oxides can be obtained. In particular, we made use of time-resolved ARPES with HHG probe to measure both the dynamics of quasiparticles over the entire Brillouin Zone of the Bi2212 compound and the dynamics of the Mott excitations involving the O 2p states lying 1.5 eV below the Fermi level. The dynamics of these high-energy excitations show a clear connection with the electron dynamics at the antinodes of the Fermi surface. This finding provides a novel ingredient for the theories of high-temperature superconductivity in copper oxides. On a complementary side, I will discuss the latest developments and the future perspectives of the T-ReX Laboratory, where novel ultrafast photon sources of EUV and XUV coherent radiation are being developed in order to perform TR-ARPES experiments on correlated materials with high statistics, high energy/momentum resolutions, and low space charge. This is made possible by the high repetition rate operation of the driving laser sources, opening the door to the long-sought TR-ARPES investigations on copper oxides performed at very low excitation levels, while accessing the entire Fermi surface.

Observation of new types of photoinduced states: dynamical states in 1D superconductors and direct observation of photoinduced spin textures in chiral magnets

I. Madan[1,2], J. Buh[1], V.V. Kabanov[1], V.V. Baranov[3], A. Mrzel[1], D. Mihailović[1,4], G. Beruto[2], Y. Murooka[2], D. McGrootherv[5], F. Carbone[2]

[1] *Complex Matter Department, Jozef Stefan Institute, Ljubljana, Slovenia*

[2] *LUMES, Institute of Physics, EPFL, Lausanne, Switzerland*

[3] *Department of Physics, University of Antwerp, 2020 Antwerp, Belgium*

[4] *Center of Excellence on Nanoscience and Nanotechnology, Ljubljana, Slovenia*

[5] *SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, UK*

The view of the ultrafast community in its intention to create and manipulate electronic phases was so far mostly concentrated on the stable and metastable electronic steady states. In this work we explore a new type of states – dynamical dissipative states, exemplified by the phase slip phenomena in 1D conventional superconductor δ-MoN. We show that the laser excitation introduces new degree of control of this multistable system. And provide an example of the new states which can only be achieved under ultrafast excitation.

Independently, we present direct Lorentz-microscopy observation of the manipulation of magnetic states in FeGe chiral magnet. Depending on experimental conditions we observe a suppression and recovery of the chiral states, an injection, a suppression, and a reorientation of skyrmion lattice fragments in the skyrmionic and ferromagnetic phases. These examples provide a strong argument for a microscopy-based approach to the systems with first-order phase transitions.

Feynman Path Integrals and Quantum Langevin Equations Over Entangled States

Andrew G. Green[1]

[1] *London Centre for Nanotechnology, University College London, 17-19 Gordon St, London, WC1H 0AH*

Entanglement is fundamental to quantum mechanics. It is central to the EPR paradox and Bells inequality. It provides one way to identify states as classical (when entanglement is weak) and is important in numerically because it provides a robust criterion to compress descriptions of many-body states. In contrast, the Feynman path integral shows that quantum transition amplitudes can be calculated by summing sequences of states that are not entangled at all. This gives a clear picture of the emergence of classical physics through the constructive interference between such sequences, and a compelling scheme for adding quantum corrections using diagrammatic expansions.

We have unified these two powerful and complementary insights by constructing Feynman path integrals over sequences of states with a bounded degree of entanglement. The resulting possibilities are broad. I will illustrate this giving an example where capturing the key physics is difficult using conventional Feynman path integrals essentially because the dominant states are entangled but simpler using our path integral over entangled states. Furthermore, this formalism may be used to develop a quantum Langevin equation for the evolution of entangled states in open systems. I will briefly develop this formalism and share some preliminary results.

[1] A. G. Green, C. A. Hooley, J Keeling, S. H. Simon,arXiv:1604.07210 (2016)
[2] P. Crowley, J. Morley, V. Oganesyan, A. G. Green in preparation

Universality manifesting through characteristic energy ratios of bound states in gapped impurity systems

R. Žitko[1], M. Fabrizio[2]

[1] *Theoretical physics, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *SISSA and CNR-IOM Democritos, Via Bonomea 265, I-34136 Trieste, Italy*

In scale-invariant critical systems the universality manifests through characteristic values of the exponents in the power-law behavior of thermodynamic quantities, with the same values for a variety of systems in the same universality class in spite of the vast differences in their physical character. These exponents are, in turn, determined through the properties of the associated fixed points (dimensions of the relevant scaling fields) in the renormalization group treatment. What about the universality in systems with a gap? We report that in systems where a quantum impurity with a non-Fermi-liquid fixed point (e.g., multi-channel Kondo model) is coupled to superconducting contacts, the sub-gap states occur at universal energy ratios which are characteristic of the associated fixed point. Anomalous power-law exponents hence turn into energy ratios when the scale invariance is broken by opening a small gap.

[1] RŽ, MF, arxiv:1606.07697

Magic Ratios of Linear Conductances of Gated Graphene Structures

A. Ramšak[1,2], T. Rejec[1,2], L. Ulčakar[2]

[1] *University of Ljubljana, Faculty for mathematics and physics, Jadranska ulica 19, 1000 Ljubljana, Slovenia*

[2] *Jožef Stefan Institute, Department for theoretical physics, Jamova 39, 1000 Ljubljana, Slovenia*

Recently a new magic ratio rule that captures the contribution of the connectivity to the conductance ratios of graphene-like cores when the coupling to the electrodes is weak and the Fermi energy coincides with the center of the HOMO-LUMO gap has been identified [1]. The rule is exact for a tight-binding bipartite lattice of identical sites with identical couplings when the Fermi energy is located at the gap center. It states that the connectivity-driven conductance ratio is simply the square of the ratio of two magic integers whose values depend only on the connectivities to the electrodes.

A comparison with available experimental values confirms the magic ratio rule qualitatively. There are several possible sources generating quantitative deviations of the magic ratio rule. We analysed the deviations due to top gate voltage pushing on-site energies away from the center of the HOMO-LUMO gap, due to the coupling to leads being non-negligible and due to the electrodes causing on-site energies on atoms to which leads are attached to deviate from on-site energies on other atoms [2]. The deviation from the ratio given by magic integers was found to become important when those parameters become of the order of the hopping integral of the molecule. For small values of those parameters, the deviation was found analytically. Furthermore, if the top gate voltage is non-zero, the molecule conducts even when both leads are attached to sites in the same sublattice, which for other perturbations is not the case. Effects due to the Coulomb electron-electron interaction and the effect of screening due to the gates seem to be most relevant for understanding of the deviation of the experimental results from the magic ratio rule [3].

[1] Y. Geng et al., J. Am. Chem. Soc. **137**, 4469 (2015).

[2] L. Ulčakar, T. Rejec, and A. Ramšak, Acta Chim. Slov. **63**, 583 (2016).

[3] T. Rejec, L. Ulčakar, A. Ramšak, J. Kokalj et al., in preparation.

Generalized eigenstate thermalization in integrable lattice models

Lev Vidmar and Marcos Rigol

Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

The generalized Gibbs ensemble (GGE) was introduced ten years ago to describe observables in isolated integrable quantum systems after equilibration [1, 2], a process we call generalized thermalization. However, the microscopic origin of generalized thermalization in integrable systems is currently still under debate.

In a system of hard-core bosons, it has been observed that eigenstates of the Hamiltonian that have similar distributions of conserved quantities also have similar expectation values of observables [3]. This phenomenon was named *generalized eigenstate thermalization* after a related phenomenon in nonintegrable systems, namely, eigenstate thermalization.

The focus of my presentation will be the paradigmatic transverse field Ising model. We study statistical weights of eigenstates in ensembles that describe observables after a quantum quench [2]. We show both analytically and numerically that, for every observable studied, nonvanishing weights are only present in a region around the system's mean energy in which eigenstates have similar expectation values of observables. These results support the generalized eigenstate thermalization scenario and provide a microscopic understanding for the general success of the GGE.

[1] M. Rigol, V. Dunjko, V. Yurovsky, and M. Olshanii, Phys. Rev. Lett. **98**, 050405 (2007)

[2] L. Vidmar and M. Rigol, J. Stat. Mech. (2016) 064007

[3] A. C. Cassidy, C. W. Clark, and M. Rigol, Phys. Rev. Lett **106**, 140405 (2011)

Manipulation of screening in Mott's insulators

D. Golež[1], P. Werner[1] and M. Eckstein[2]

[1]*Department of Physics, University of Fribourg, 1700 Fribourg, Switzerland*

[2] *Max Planck Research Department for Structural Dynamics, University of Hamburg-CFEL, 22761 Hamburg, Germany*

We present a study of the screening dynamics in the Mott insulators within the extended Hubbard model. First the effects of the non-local correlations on the equilibrium spectral properties, like plasmon satellites structures, will be discussed. We demonstrate different examples how by applying the pulse or AC field one can enhance long-range charge fluctuations, which leads to the enhanced subgap response of the susceptibility. As the extreme example we show how system can be trapped in the negative temperature state by proper manipulation of the screening environment.

Interplay between different orders in 1T-TaS_2

I. Vaskivskyi[1], J. Ravnik[2], T. Mertelj[1], Y. Gerasimenko[2], D. Svetin[2], L. Le Guyader[3,4], T. Chase[4], A. Reid[4], R. Li[4], X. Wang[4], H. Dürr[4], D. Mihailović[1,2]

[1] *Center of Excellence on Nanoscience and Nanotechnology – Nanocenter (CENN Nanocenter), Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[3] *Spectroscopy & Coherent Scattering, European XFEL GmbH, Hamburg, Germany*

[4] *SLAC National Accelerator Laboratory, Menlo Park, USA*

Huge experimental[1-4] and theoretical[5] effort is being invested in understanding nature and properties of the recently discovered long-lived photoinduced hidden state (H) in 1T-TaS2. Different approaches, such as transport measurements[1], optical pump-probe spectroscopy[2], time-resolved ARPES[3], STM and STS[4] were successfully applied. Each of the methods has its pros and cons: while STM can reveal the real-space structure of the H state, it does not provide time-resolution and does not allow studying the dynamics of the phase transition. On the other hand, time-resolved optical spectroscopy and ARPES do not provide direct information on the structure of the material.

I will summarize recent results obtained by different techniques and compare them with the first preliminary data from time-resolved electron diffraction, which reveals the evolution of CDW pattern through the phase transition to the H state.

[1] I. Vaskivskyi et al. Nat. Commun. 7, 11442 (2016)
[2] L. Stojchevska et al. Science 344. 6180 (2014)
[3] I. Avigo et al. Proc. SPIE Spintronics IX, 9931 (2016)
[4] L. Ma et al. Nat. Commun. 7, 10956 (2016)
[5] S. Brazovskii J. Supercond. Nov. Magn. 4, 28 (2015)

Pumping approximately integrable models

Z. Lenarčič, F. Lange, and A. Rosch

Institute for theoretical physics, University of Cologne, Germany

When a degree of freedom is approximately protected by a conservation law even weak perturbations can cause strong response in that quantity and drive the many-particle system far from its equilibrium steady state. A platform with infinitely many (quasi-)local conserved quantities is provided by integrable quantum models, which are theoretically interesting yet experimentally always only approximately realized. I will present our theory of weakly open driven integrable models on an example of 1D Heisenberg XXZ chain. As a possible concrete experimental confirmation of our theory I will suggest novel heat and spin pumps exploiting the property that these currents are approximately conserved quantities within the model considered: only weak THz laser radiation should induce huge heat and spin currents. Furthermore, we will argue that the concept of the generalized Gibbs ensembles, introduced to describe the relaxation of closed integrable models, can be approximately but efficiently used even in the presence of a weak openness and driving.

[1] F. Lange, Z. Lenarcic, and A. Rosch, arXiv:1608.03563 (2016)

Correlated-electron transport in hcp-Fe under extreme conditions present in inner Earth Core

J. Mravlje

Department of Theoretical Physics, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia

The Earth's magnetic field is essential for the life as it protects the ozone layer from the solar wind. The magnetic field exists due to the geodynamo mechanism which is driven by convective processes in the liquid iron external core. Sufficiently low thermal conductivity is essential for the existence of the convection. Recently it has been discovered that the electron-phonon interaction is less efficient than believed earlier [1] and that the thermal conductivity is about 5 times larger than assumed in geophysical models, which questions what ensures the stability of the geodynamo. Work [2] suggested electron-electron interactions could play an imporant role. It considered hcp-Fe, believed to be the main constituent of the Earth's inner core, under 300 GPa and 6000K present there and found a non-Fermi liquid behavior and large resistivity of the same magnitude as the electron-phonon one. We repeated the same calculations more precisely [3] and found that the hcp-Fe behaves as a Fermi liquid and that the alculated resistivity is about 1/4th of the one found due to the electron-electron scattering due to numerical mistakes in [2], which led to retraction of the paper. We calculated also thermal conductivity. The effect of electron-electron scattering on thermal conductivity is due to a breakdown of Wiedemann-Franz law larger. The calculated thermal conductivity is 540W/mK which is similar to the one obtained from the electron-electron scattering 300W/mK [4], which suggests electron-electron scattering plays a non-negligible role in the dynamics of the Earth's core.

[1] M. Pozzo, C. Davies, D. Gubbins, and D. Alfe, Nature 485, 355,(2012).

[2] P. Zhang, R.E. Cohen, and K. Haule, Nature 517, 605 (2015).

[3] L. V. Pourovskii, J. Mravlje, A. Georges, S.I. Simak, I. A. Abrikosov, arXiv:1603.02287 (2016).

[4] M. Pozzo, C. Davies, D. Gubbins, and D. Alfe, Earth and Planet. Sci. Lett. 393, 159 (2014.

Wednesday, 21 December

Morning Session

9:00 - 9:30	**A. Potočnik:** Analog Quantum Simulations using Superconducting Circuits
9:30 - 10:00	**V. Nasretdinova:** Time-resolved studies of the photoinduced metastable states in the unusual CDW molybdenum oxide Mo_8O_{23}
10:00 - 10:30	**Y. Gerasimenko:** Nanoscale imaging of hidden state in 1T-TaS_2
10:30 - 11:00	**Coffee break**
11:00 - 11:30	**J. Ravnik:** Coherent Control of Switching to the Hidden State in 1T-TaS_2

Analog Quantum Simulations using Superconducting Circuits

A. Potocnik[1], A. Bargerbos[1], M. C. Collodo[1], S. Gasparinetti[1], F. A. Y. N. Schröder[1], C. Creatore[2], A. W. Chin[2], C. Eichler[1], A.Wallraff[1]

[1] *Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland*

[2] *Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom*

Superconducting circuits have seen a remarkable progress in the last decade and are now at the heart of areas such as quantum information processing, quantum optics, quantum cryptography and quantum simulations. In particular quantum simulations with superconducting circuits are becoming increasingly popular since the size of the quantum system that can be fabricated on a chip is close to the limit of what is possible to be simulated with classical computers. In quantum simulators a versatile control of artificial two level systems is utilized to simulate a specific Hamiltonian either by a sequence of discrete steps (digital quantum simulations) or by a dedicated fixed arrangement of tunable elements on a chip (analog quantum simulations) [1]. We employ an analog quantum simulator to shed more light a long standing problem of photosynthesis in light harvesting systems. A surprising high energy transport efficiency of nearly 100% and recent observation of long coherences using ultrafast optical spectroscopy led many people to argue that quantum or coherent effects may play a role in energy transport even at room temperature [2]. To experimentally investigate some of the proposed mechanisms behind the excitation transport we built an analog quantum simulator as shown in Fig. 1. Our quantum processor simulates a prototypical system of three chromophores (two-level systems) with qubit Q1 and qubit Q2 coupled to the excitation source (transmission line depicted in purple) and qubit Q3 to the excitation sink emulated by Purcell decay through the resonator (depicted in orange). In addition we apply an engineered classical noise with arbitrary power spectral density to qubit Q2 in order to simulate Markovian and non-Markovian environments as well as excite the system with an incoherent source which mimics the sunlight in the photosynthetic process.

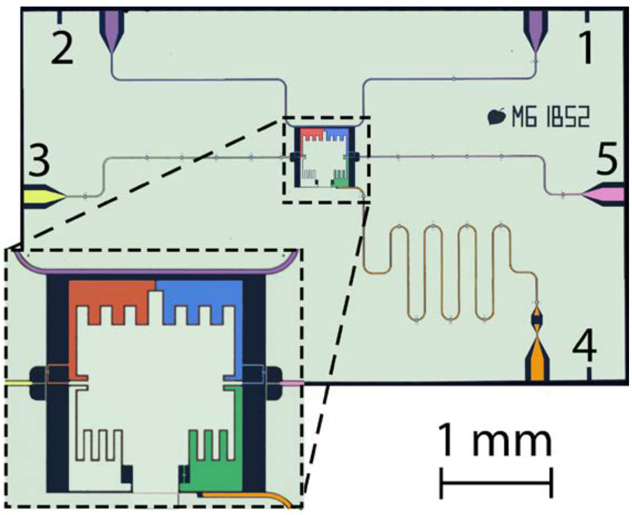

Figure 1: False-colored micrograph of an analog quantum processor with three qubits (Q1 shown in red, Q2 in blue and Q3 in green color) designed to simulate light harvesting processes in photosynthetic protein complexes

[1] Houck, et al. Nat Phys 8, 292–299 (2012).

[2] Fassioli, et al., J. R. Soc. Interface 11, (2014).

Time-resolved studies of the photoinduced metastable states in the unusual CDW molybdenum oxide $\mathbf{Mo_8O_{23}}$

Venera Nasretdinova[1], Miloš Borovšak[2] , Tomaž Mertelj[1,2], Petra Šutar[1], Damjan Svetin[1,2], Jernej Mravlje[1], Dragan Mihailović[1,2,3]

[1] *Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *Center of Excellence on Nanoscience and Nanotechnology – Nanocenter (CENN Nanocenter), Jamova 39, SI-1000 Ljubljana, Slovenia*

[3] *Jozeph Stefan International Postgraduate School, Jamova 39, SI-1000 Ljubljana, Slovenia*

Recent nonequilibrium studies of the charge density wave (CDW) system $1T$-TaS_2 have demonstrated the possibility of ultrafast optical switching from a commensurate CDW state to a state unreachable under continuous change of parameters such as temperature, doping or pressure. [1]. The outstanding stability of this so-called “hidden” state to external perturbations motivates further search of materials exhibiting such phenomena. While the exact conditions required for switching to a hidden state in CDW system are still a subject of hot debate [2], it seems that non-trivial coupling of the CDW to external degrees of freedom may be one of requirements for stabilizing metastability and leading to topological protection in the form of CDW domains[3]. The low-dimensional molybdenum oxide Mo_8O_{23} (i.e. $MoO_{3-0.125}$, MoO_3 being an insulator) might be an interesting candidate for exploring metastable states. The high-temperature conductivity of this compound has quasi-one-dimensional character (σ_a/σ_b 102, σ_a/σ_c 10), whereas below 100 K the conductivity demonstrate two-dimensional character similar to TaS_2[4]. Mo_8O_{23} has a phase transition associated with the emergence of a CDW above room temperature, $TCDW \approx 350$ K while the resistivity shows a hysteretic behavior above 300 K which indicates the presence of metastability. Room-temperature DFT calculations show strong asymmetry of electronic and hole bands which can lead to a photodoping effect. These properties are similar to that of $1T$-TaS_2 where a photodoping process is thought to be important for the optical control of switching. Unusual coupling between CDW and lattice degrees of freedom in Mo_8O_{23} is discussed in literature [5] in relation with incommensurate-commensurate phase transition at 285 K. In this transition CDW wave-vector locks to the lattice. However x-rays studies also show coordinated rotation of MoO_6 octahedra around q_{ICDW} in the commensurate state[6,7].

We present the first results of the search for the photoinduced metastable states in single crystals of Mo_8O_{23}. Single ultrashort (50-fs) optical pulse of critical fluence induces visible change of the light scattering at the incident spot, while short exposure to multiple (10000) 50-fs pulses of critical fluence also alters polarization dependendence of the transient reflectivity maxima. While experiments are done at low temperatures below 10 K, the induced changes are at least partially stable above room temperature, up to the $TCDW \approx 350$ K. We interpret the observed phenomena as photoinduced non-thermal reorientation of MoO6 octahedra to novel metastable configuration and discuss possible mechanisms of such reorientation. We note that recently the cooperative dynamics of MnO_6 octahedra, akin to that of MoO6, was shown to drive a photoinduced transition to a hidden metallic phase in LCMO[8].

[1] L Stojchevska et al. Science 344 (2015) 177-180.

[2] D. Svetin et al. http://arxiv.org/abs/1603.06214

[3] Y. Gerasimenko et al, present volume

[4] M. Sato et al. J. Phys. C: Solid State Phys. 19 (1986) 3059 .

[5] J. Pouget in Schlenker, C., Ed. Low-Dimensional Properties of Molybdenum Bronzes and Oxides; Reidel: Dordrecht, The Netherlands (1989) .

[6] M. Sato et al. J. Phys. C: Solid State Chem. 46 (1987) 40-46.

[7] H.Sowa et al. Phase Transitions, 47 (1994)1-8.

[8] J. Zhang et al. Nature Materials 15, 956–960 (2016)

Nanoscale imaging of hidden state in 1T-TaS_2

Ya. A. Gerasimenko[1], I.Vaskivskyi[1], M. Litskevich[3], D.Mihailovic[1,2]

[1] *Center of Excellence on Nanoscience and Nanotechnology Nanocenter (CENN Nanocenter), Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[3] *Department of General and Applied Physics, Moscow Institute of Physics and Technology, Institutski 9, 141700, Dolgoprudny, Russia*

Recently ultrafast switching to an extremely long-living metastable state was observed in 1T-TaS_2 [1]. The switching occurs from an insulating charge density wave (CDW) to a metallic-like state with a single ultrafast optical [1] or electric pulse [2-4]. The final state was ascribed to hidden for it appeared different from other known states in 1T-TaS_2, judging by the unique frequency of the CDW amplitude mode[1]. The latter cements CDW involvement, suggesting it the object to study in details.

Previously, transient CDW behavior was studied in time-resolved TEM measurements[5], where indeed metastable CDW orders were found, but at fluences higher than that for hidden state. Furthermore, domain structure could not be resolved in details. Domain structure was observed in STM studies of electrically-switched hidden state [3,4], however CDW order was not identified. The domains structure was ascribed to supercooled variant of equilibrium nearly-commensurate CDW state, based on domain sizes [4].

Here we combine in situ ultrafast optical switching with STM to study microscopic structure of the proposed hidden state in 1T-TaS_2 both on atomic and domain scales. The straightforward evidence for hidden nature of the state is found in atomic resolution images, where CDW is found rotated with respect to atomic lattice at the angle different from any equilibrium ones. For the associated domain structure, in addition to single domain periodicity expected in equilibrium [6], its higher harmonics are found. Their relaxation during STM imaging cements their relation to "excited" hidden state. Together these observations for the first time reveal the microscopic picture of hidden state created at essentially non-equilibrium conditions.

This work was supported by ERC Advanced Grant Trajectory. ML was partially supported by RFBR grant 16-32-00924.

[1] L. Stojchevska et al., Science 344, 177180 (2014)
[2] I. Vaskivskyi et al., Nat. Commun. 7, 11442 (2016)
[3] D. Cho et al., Nat. Commun. 7, 10453 (2016)
[4] L. Ma et al., Nat. Commun. 7, 10956 (2016)
[5] T.R.T Han et al., Science Advances 1, e1400173 (2015)
[6] K. Nakanishi et al., JPSJ 43, 1509 (1977)

Coherent Control of Switching to the Hidden State in 1T-TaS_2

J. Ravnik[1], I. Vaskivskyi[2], P. Sutar[1], T. Mertelj[1], D. Mihailovic[1,2]

[1] *Complex Matter Department, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*

[2] *Center of Excellence on Nanoscience and Nanotechnology – Nanocenter (CENN Nanocenter), Jamova 39, SI-1000 Ljubljana, Slovenia*

Here we report on time evolution of switching to the hidden state in 1T-TaS2 shortly after the arrival of wirte pulse. As it was shown earlier, 1T-TaS2 can be switched from an insulating commensurate charge density wave state to a conducting metastable hidden quantum state at low temperatures [1]. The phase transition is induced by a single 35 fs laser pulse [1]. Because of the large resistivity changes and remarkable stability, the system became a potential candidate for future ultrafast nonvolatile memory devices.

Since the hidden state is stable on a very long time scale, the time evolution of switching cannot be measured directly by pump-probe measurements at low temperatures. The extrapolation of measured relaxation times shows us that at 160 K the lifetime of the hidden state is about a microsecond [2]. We made a series of pump-probe measurements to show that the hidden state indeed exists at such high temperatures and to exclude possible heating effects. Low laser repetition rate was used, to let the sample relax between the pulses. We performed three pulse write-pump-probe experiments and have directly measured the time evolution of the hidden state. The observed time of switching was of the order of a few picoseconds. Moreover, by exciting the sample with a write pulse arriving after the pump pulse, we can see that the phonon frequency changes in about one oscillation period, i.e. less than half a picosecond.

The work was supported by ERC ADG Trajectory (GA320602).

[1] L. Stojchevska et. al., Ultrafast Switching to a Stable Hidden Quantum State in an Electronic Crystal, Science 344, 177, (2014).

[2] I. Vaskivskyi et. al., Controlling the metal-to-insulator relaxation of the metastable hidden quantum state in 1T-TaS2, Science Advances 1, 6, (2015).

Conference schedule

	Saturday, 17. 12	Sunday, 18. 12	Monday, 19. 12	Tuesday, 20. 12	Wednesday, 21. 12
$9^{00} - 9^{30}$		Registration II	D. Mihailović	C. Gianetti	A. Potočnik
$9^{30} - 10^{00}$		Opening	C. Gadermaier	F. Cilento	V. F. Nasretdinova
$10^{00} - 10^{30}$		U. Bovensiepen	J. Demšar	I. Madan	Y. Gerasimenko
$10^{30} - 11^{00}$		F. Parmigiani	Coffee break	Coffee break	Coffee break
$11^{00} - 11^{30}$		Coffee break	P. Prelovšek	A. Green	J. Ravnik
$11^{30} - 12^{00}$		T. Tohyama	M. Mierzejewski	R. Žitko	Closing
$12^{00} - 12^{30}$		S. Ishihara	F. Heidrich-Meisner	A. Ramšak	
$16^{30} - 17^{00}$		M. Rigol	M. Eckstein	L. Vidmar	
$17^{00} - 17^{30}$		P. Werner	J.H. Mentink	D. Golež	
$17^{30} - 18^{00}$		Coffee break	Coffee break	Coffee break	
$18^{00} - 18^{30}$	Registration I	T. Prosen	V.V. Kabanov	I. Vaskivskyi	
$18^{30} - 19^{00}$	Registration I	M. Medenjak	T. Mertelj	M. Capone	
$20^{30} - 21^{00}$		L. Zadnik	J. Kogoj	Z. Lenarčič	
$21^{00} - 21^{30}$		I. Kukuljan		J. Mravlje	