Nonequilibrium Phenomena in Quantum Systems

BOOK OF ABSTRACTS

Ambrož, Krvavec, Slovenia, December 17th – 20th 2017

Jožef Stefan Institute
Ljubljana Slovenia

University of Ljubljana
Faculty of Mathematics and Physics

Nanocenter

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Organized by:

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A non-Equilibrium approach to the optical spectroscopy of high-temperature superconductors

F. Parmigiani

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International Faculty - University of Cologne
Elettra Sincrotrone Trieste

Non-equilibrium spectroscopies of high temperature superconductors have evolved in the last two decades from avant-garde studies to a crucial tool for understanding the physics of high temperature superconductors. In particular, the possibility of obtaining both spectral and temporal information simultaneously leads to insights that are complementary (and in some instances beyond to) those attainable by conventional equilibrium experiments. This presentation is focused on the still unresolved problem of the origin of the pseudo-gap in cuprates, one of the major open issues about copper-oxides based superconductors. Indeed, the ubiquitous phenomenology of the pseudo-gap, occupying a wide region of the phase diagram, is not understood yet. Its comprehension could provide clue information about the microscopic mechanisms of these materials and their phase diagram. We investigate the pseudo-gap with non-equilibrium approach, that allows to disentangle the intertwined degrees of freedom (carrier, lattice. long range order) by their timescale.

On the origin of hidden states metastability in 1T-TaS_2

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Observation of the long-living metastable emergent states [1, 2] induced by an ultrafast optical pulse opens the opportunity to study non-equilibrium phase transitions with unprecedented resolution. It also gives access to the single outcome rather than stroboscopic measurements and, hence, allows tracking the evolution of individual objects. By combining ultrafast optical excitation and low-temperature scanning tunneling microscope we were able to observe the long-range order in the textured hidden state in 1T-TaS_2 and got insight into the nature of the transition, which appears to be of the Berezinsky-Kosterlitz-Thouless type [3].

We will focus on the various types of constraints that govern the formation and relaxation of hidden metastable states on nano- and meso-scales. In particular, we will talk about vortex annihilation rules, inhomogeneous domain growth and kinetic arrest.

As an outlook, we will discuss the role of entropy in ultrafast transitions and possibility to observe quantum processes in relaxation.

[1] L. Stojchevska et al., Science 344, 177–180 (2014).
[2] J. Zhang et al., Nat. Mater. 15, 956 (2016).
[3] Ya. A. Gerasimenko, I. Vaskivskyi, D. Mihailovic, arXiv:1704.08149v2.

Modeling of networks and globules of charged domain walls observed in pump and pulse induced states in 1T-TaS_2

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Experiments on optical and STM injection of carriers in layered 1*T*-TaS_2 revealed the formation of nanoscale patterns with networks and globules of domain walls [1-4]. This is thought to be responsible for the metallization transition of the Mott insulator and for stabilization of a "hidden" state.

In response to these challenges, I shall present studies of the classical charged lattice gas model emulating the superlattice of polarons ubiquitous to 1*T*-TaS_2 [5]. The injection pulse was simulated by introducing a small concentration of voids which subsequent evolution was followed by means of Monte Carlo cooling. Below the detected phase transition, the voids gradually coalesce into domain walls forming locally connected globules and then the global network leading to a mosaic fragmentation into domains with different degenerate ground states. The obtained patterns closely resemble the experimental STM visualizations [1-4]. The surprising aggregation of charged voids is understood by fractionalization of their charges across the walls' lines. In comparison with the positive (by voids) doping with predominating 3-wall vertices, the negative (by interstitials) one makes 4-wall vertices also quite probable. With increasing screening length, the resulting walls' structure tends to be universal and independent of the doping sign.

I shall also discuss qualitatively the issues of the network stability coming from the charge conservation and from topological constraints. The last ones depend on the "vorticity" of the net vertices.

[1] Y.A. Gerasimenko, I. Vaskivskyi, and D. Mihailovic, arXiv:1704.08149 (2017).
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[3] D. Cho et. al., Nat. Commun. 7, 10453 (2016).
[4] I. Vaskivskyi et. al., Nat. Commun. 7, 11442 (2016).
[5] P. Karpov, S. Brazovskii, arXiv:1709.01912 (2017).

Photoinduced states in 1T-TaS_2 reached by extreme fluences

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1T-TaS_2 is a very versatile system, which supports a plethora of different equilibrium phase states, including different charge density wave (CDW) states, superconductivity [1] and an unusual quantum spin liquid [2] amongst others. The system attracted a lot of attention with the discovery of a metallic textured hidden (H) state, with lifetimes exceeding the age of universe at low temperatures [3]. The crystal can be switched to the H state by using a single ultrafast laser pulse (1 mJ/cm^2), where the transition takes place in less than 500 fs [4]. Later examinations show that the crystal can be switched to a metallic state also by an electrical pulse [5] or voltage pulse from STM tip [6]. Although these states seem identical, careful analysis of 2D-FFT spectra of STM images show us that they are different and are also distinct from any known equilibrium states [7]. Furthermore, another long lived glass – like amorphus metastable state was recently found by exciting it at slightly different conditions [8].

Here we report on our recent discovery of yet another photoinduced state, where much higher laser fluences (100 mJ/cm^2) were used. At these extreme fluences the top layer of the crystal transforms to a possibly new phase, which appears in triangles throughout the surface of the crystal as seen with STM. The newly found phase doesnt seem to have a CDW present, but a very weak CDW modulation can sometimes be observed, which we attribute to the charge modulation from bottom layers. When fluence is high enough, the whole surface transforms to the new state and we can observe a very weak stripe – like modulation of the new state with period of about 17 nm, which persists unchanged on areas larger than 1 μm^2. The state is stable (no changes seen in a week), but can be further modulated by applying voltage pulses with STM tip, where we can observe the creation of the well known H state, as well as some interesting 6-fold topological defects on the stripes in our new phase.

The work was supported by ERC ADG Trajectory (GA320602) and the Slovenian Research Agency (young researcher, P10040).

[1] B. Sipos et al., Nature Materials 7, 960–965, (2008).
[2] M. Klanjsek et. al., Nature Physics 13, 1130–1134 (2017).
[3] L. Stojchevska et. al., Science 344, 177 (2014).
[4] J. Ravnik et. al., arXiv:1711.09710 (2017).
[5] I. Vaskivskyi et. al., Science Advances 1, 6 (2015).
[6] L. Ma et. al., Nature Communications (2016).
[7] Y. A. Gerasimenko et. al., arXiv:1704.08149 (2017).
[8] Y. A. Gerasimenko et. al., unpublished (2017).

Theoretical modeling of the non-equilibrium amorphous state in 1T-TaS_2

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1T-TaS_2 exhibits a range of physical phenomena, including superconductivity, various charge density wave states [1] and a spin liquid at low temperatures [2]. Stojchevska et. al. [3] have shown that apart from equilibrium phases there exists another metastable hidden (H) state, which can only be obtained out of equilibrium via excitation with an ultra-short laser pulse. Recent experiments [4] have shown that there is yet another non-equilibrium phase, which can be achieved via higher fluence excitation, significantly larger than required for obtaining the H state. The phase exhibits ordering properties that are similar to glass and is therefore dubbed as an amorphous (A) state. Recent work by Karpov et. al. [5] has shown that the equilibrium commensurate (C) state may be considered as the ground state of classical spinless polarons interacting via a screened Coulomb potential. The concentration of polarons in C state should be exactly 1/13. It was also shown that the H state can be considered as a system of interacting polarons where the concentration of polarons is slightly lowered. In dealing with A state we considered a similar model of interacting polarons with the filling factors between 1/13 and 1/9. We have found that A state corresponds to a frustrated Coulomb system, where there is no order-disorder phase transition. Rather than the formation of a polaron lattice, or a domain walled structure, here no lattice is formed. Yet the system is still highly correlated. These correlations can be described using the concept of hyperuniformity, where the variance of the number of particles grows with distance as r^n, where $n < d$ and d is the dimensionality of the system.

The work was supported by ERC ADG Trajectory (GA320602) and the Slovenian Research Agency (young researcher, P10040).

[1] B. Sipos, A. F. Kusmartseva, A. Akrap, H. Berger, L. Forró, and E. Tutiš, Nature Materials **7**, 960 (2008).
[2] M. Klanjšek, A. Zorko, J. Mravlje, Z. Jagličić, P. K. Biswas, P. Prelovšek, D. Mihailovic, D. Arčon, and others, Nature Physics (2017).
[3] L. Stojchevska, I. Vaskivskyi, T. Mertelj, P. Kusar, D. Svetin, S. Brazovskii, and D. Mihailovic, Science **344**, 177 (2014).
[4] Y. A. Gerasimenko et. al., unpublished (2017).
[5] P. Karpov and S. Brazovskii, arXiv Preprint arXiv:1709.01912 (2017).

Ultrafast Magnetism in High Magnetic Fields

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We show that applying magnetic fields up to 30 T has a dramatic effect on the ultrafast spin dynamics in ferrimagnetic GdFeCo [1] and TbFeCo. Upon increasing the field beyond a critical value, the dynamics induced by a femtosecond laser excitation strongly increases in amplitude and slows down significantly. Such a change in spin response is explained by different dynamics of the Gd (Tb) and FeCo magnetic sublattices following a spin-flop phase transition from a collinear to a noncollinear spin state. Using thermodynamics in collaboration with Prof. A. K. Zvezdin we analyses H-T phase diagram for the alloys in the vicinity of the compensation temperature and show that the observed dynamics can be understood in terms of kinetics of first and second order phase transitions.

[1] J. Becker et al., Phys. Rev. Lett. 118, 117203 (2017).

Néel Vector Dynamics of Mn_2Au Probed by Time Domain Spectroscopy

V. Yu. Grigorev[1,2], N. Bhattacharjee[1], A. Sapozhnik1[,2], S. Bodnar[1], S. Y. Agustsson[1], J. Cao[1], D. Dominko[1], O. Gommonay[1], M. Jourdan[1,2], and J. Demsar[1,2]

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Antiferromagnetic (AFM) materials are attracting a lot of interest in the field of spintronics due to their insensitivity to external magnetic fields and potentially ultrafast switching. Among them Mn_2Au is of special interest due to its high Néel temperature (~1500K), strong spin-orbit coupling and high conductivity [1,2]. One of the central questions for potential ultrafast manipulation/switching of the AFM order for novel spintronic memory devices is to determine characteristic time scales (collective mode frequencies). To shed light on these, we performed linear time-domain THz spectroscopy, where the temperature dependent optical conductivity reveals the presence of a 1 THz mode, which softens upon increasing temperature. This mode can be attributed to an in-plane antiferromagnetic resonance (AFMR), driven by the Néel spin-orbit torque.

To investigate the Néel vector and/or its dynamics we follow a recently demonstrated approach, where a weak birefringence induced by symmetry breaking due to AFM ordering can be resolved in a pump-probe configuration, thereby determining the Néel vector direction [3]. Using this method we were able to determine the Néel vector direction, which is found in agreement with previous theoretical [1] and experimental results [4,5]. Furthermore, the time resolved character of this technique allowed us to observe a shift of its direction on a picosecond time scale, which we attribute to the ps strain induced by photoexcitation.

[1] S. Khmelevskyi and P. Mohn, *Appl. Phys. Lett.* **93**, 162503 (2008).
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[3] P. Saidl, et al., *Nature Photonics* **11**, 91 (2017).
[4] A. A. Sapozhnik, R. Abrudan, Yu. Skourski, M. Jourdan, H. Zabel, M. Kläui, and H.-J. Elmers, *Phys. Status Solidi* RRL, **11** (2017).
[5] V.M.T.S. Barthema, C.V. Colinb, R. Haettelb, D. Dufeub, D. Givord, *Journal of Magnetism and Magnetic Materials* **406**, 289 (2015).

Spectral Tunability of Mechanisms of Laser-induced Spin Dynamics in Ferromagnetic Semiconductor $CdCr_2Se_4$

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We report on study of spin dynamics induced by femtosecond laser pulses in ferromagnetic semiconductor $CdCr_2Se_4$ with the band gap of 1.4 eV. We reveal that the pulses are able to trigger oscillations of the magneto-optical Faraday rotation in this material if the magnetic field is applied at an angle to the sample normal. The frequency of the oscillations is in the GHz range being a linear function of the magnetic field, which corresponds to ferromagnetic resonance (FMR). Tuning the photon-energy of the pump pulses we reveal two different mechanisms inducing FMR precession in this material. In the case of pumping from the valence band deep into the conduction band (photon energy 3.1 eV) the phase of the spins oscillations is not sensitive to the polarization of the pump, but can be reversed over 180-degrees by changing the polarity of the applied magnetic field. This mechanism is due to ultrafast laser-induced heating, which requires a strong optical absorption in the material and becomes inactive if the pump photon energy is below the band-gap. Tuning the photon energy in a wide range from 0.88 to 3.1 eV allows revealing the second mechanism of spin excitation with the maximum at 1.2 eV. Contrary to the laser-induced heating, this excitation mechanism is pump polarization dependent being the most efficient if the pump is circularly polarized. The phase of the spin oscillations is independent on the polarity of the applied magnetic field, but changes by 180-degrees by changing the helicity of light. It is suggested that the effect is due to spin transfer torque experienced by the network of the ordered Cr^{3+}-spins as a result of resonant excitation of electrons from Se^{4+}-states with the strong spin-orbit interaction to the states of the Cr^{3+} ions.

Ultrafast electron dynamics in pristine and chemically doped 1*T*-TaS_2

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1*T*-TaS_2 is a layered transition metal dichalcogenide that exhibits a manifold of electronically and structurally ordered phases [1,2]. Beside the rather well understood charge density wave physics in this system, the exact role of electronic correlations in electronic gap formation is discussed for decades [3]. Performing time-resolved photoemission experiments, we identified a spectroscopic signature of such correlations which also exhibits dynamics which are faster than expected [4]. Beside this specific signature, the electron dynamics in the insulating low temperature phase are clearly different from the metallic behavior at high temperatures and appear to be of localized nature. Chemical isovalent doping (1*T*-$TaS_{2-x}Se_x$, x = 0.15-0.6) slows down these dynamics and quenches the correlation signature.

[1] B. Sipos et al., *Nature Mater.* **7**, 960 (2008).
[2] L. Stojchevska et al., *Science* **344**, 177 (2014).
[3] T. Ritschel et al., *Nature Phys.* **11**, 328 (2015).
[4] M. Ligges et al., *arXiv:1702.05300.*

Non-equilibrium dynamics in the 1D Fermi-Hubbard model

F. Heidrich-Meisner[1]

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

This talk will cover two aspects of non-equilibrium dynamics in the 1D Fermi-Hubbard model related first, the non-equilibrium mass transport of doublons and second, the dynamics of doublon-holon pairs. The first example deals with a set-up that can be studied with cold atomic gases. We study a cloud of fermionic atoms trapped in an optical lattice and induce dynamics by quenching the trapping potential to zero. Our main interest is in the quantum distillation mechanism [1], which is the dynamical separation of doublons and singlons in the ensuing sudden expansion into the empty optical lattice. Under ideal conditions, this process can be used to purify a band insulator, thus creating a low-entropy region. We extend the theoretical analysis to two-leg ladder systems and identify the differences with chains [2]. Moreover, I will comment on an ongoing experimental effort [3] to observe the quantum distillation with fermions.

In the second part of the talk, I will consider a simplified set-up to model a Mott-in-insulator hetero-structure coupled to leads. We investigate the dynamics of doublon-holon pairs, created in the Mott insulating region. These pairs can be separated by a voltage and we aim to identify optimal regimes to avoid recombination before the pairs leave the correlated structure and are drawn into the leads [4]. We discuss this set-up in the context of strongly-correlated heterostructures as a platform for future solar cell applications.

[1] F. Heidrich-Meisner et al., Phys. Rev. A 80, 041603(R) (2009).
[2] J. Herbrych, A. Feiguin, E. Dagotto, F. Heidrich-Meisner et al., Phys. Rev. A 96, 033617 (2017).
[3] S. Scherg, T. Kohlert, P. Bordia, J. Stolpp, J. Herbrych, F. Heidrich-Meisner, M. Aidelsburger, U. Schneider, I. Bloch, in preparation.
[4] J. Herbrych, A. Nocera, A. Feiguin, E Dagotto, F. Heidrich-Meisner, in preparation.

Finite-temperature properties of Heisenberg model on a triangular lattice

P. Prelovšek[1,2] and Jure Kokalj[3,1]

[1] *J. Stefan Institute, Ljubljana*
[2] *Faculty of Mathematics and Physics, University of Ljubljana*
[3] *Faculty of Civil Engineering and Geodesy, University of Ljubljana*

Heisenberg model on a triangular lattice has been a candidate for the low-temperature spin liquid since the first speculation by P. Anderson in 1973. Still many important question remain open, in particular those involving low-temperature spin dynamics and the role of additional frustration. We present numerical finite-T results for static quantities and dynamical structure factor obtained on lattices up to 30 sites. In contrast to square-lattice results the specific heat reveals two scales, a broad shoulder at scale T ~ 0.7 J and a sharper maximum at coherence T ~ 0.2 J. In the intermediate region, the dynamical structure factor is sensitive on additional frustration with next-neighbor exchange confirming the possibility of spin liquid without any long-range ordering. The emergent spin-lattice relaxation rate $1/T_1$ in the latter case decreases with lowering T, qualitatively consistent with expectations for a spin liquid.

Integrable Trotterization: Local Conservation Laws and Boundary Driving

M. Vanicat[1], L. Zadnik[1], T. Prosen[1]

[1]*Faculty of Mathematics and Physics, University of Ljubljana*

I will present a general procedure to construct an integrable real-time trotterization of interacting lattice models. As an illustrative example we will consider a spin-1/2 chain, with continuous-time dynamics described by the isotropic Heisenberg Hamiltonian. In the case of periodic boundary conditions, I will present the construction of a hierarchy of local conservation laws, equipped with a boost operator. I will also describe an exact solution of the boundary driven problem. Here the bulk dynamics is described by the aforementioned trotterization, while the boundaries are stochastically coupled with an environment. This simple trotterization scheme, either in closed or open framework, could prove to be a useful tool for experimental simulations of the lattice models in terms of the trapped ion and atom-optics setups.

[1] M. Vanicat, L. Zadnik, T. Prosen, *to be published.*

Monday, 18 December

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Time resolved photoelectrons spectroscopy of novel materials for optoelectronic applications

L. Perfetti

Laboratoire de Solides Irradiés, Ecole Polytechnique, 91128 Palaiseau cedex, France

I will review our recent investigations of semiconducting materials at the focus of optoelectronic research. We measure the surface of $CH_3NH_3PbI_3$ single crystals by making use of two-photon photoemission spectroscopy. By these means, we explicitly discriminate the initial thermalization of the electrons from slower dynamical processes. The picosecond localization of excited electrons in degraded $CH_3NH_3PbI_3$ samples is consistent with the progressive reduction of photoconversion efficiency in operating devices. In the second part of the seminar I will discuss the dynamics of hot carriers in InSe. The electrons excited by photons of 3.1 eV experience a manifold relaxation. First, they thermalize to the electronic states degenerate with the M valley within 0.35 ps. Subsequently, the electronic cooling is solely dictated by Froelich coupling to phonon of small momentum transfer. Ab-initio calculations of the electron-phonon coupling are in excellent agreement with the observed dynamics.

Transient band gap enhancement in the excitonic insulator phase of Ta_2NiSe_5 upon photoexcitation

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It has been proposed in 1961 by Mott that a semimetal may be unstable towards an insulating ground state, when electrons and holes bind together through the Coulomb interaction and form excitons, which are not able to carry a current [1]. On this basis, it was elaborated a few years later that both a semimetal and a semiconductor can undergo this phase transition [2]. In the former case, the free charge carrier density must be low enough, such that the screening of Coulomb interaction is weak, and in the latter case, the binding energy of the exciton must be larger than the gap, such that the semiconductor gains energy by forming excitons. Eventually, the phase transition occurs at low temperature, when the excitons condense in a macroscopic state, giving rise to the so-called excitonic insulator phase. Experimental observation of this phase has proven to be very challenging since its theoretical prediction.

By using time- and angle-resolved photoemission spectroscopy, we show that the band gap of the semiconductor Ta_2NiSe_5 [3] can be transiently increased on the sub-picosecond timescale with an ultrashort infrared laser pulse. We attribute this effect to the excitonic insulator phase taking place in this material at low temperature. Our result suggests that for a few hundreds of femtoseconds, an out-of-equilibrium phase takes place upon photoexcitation in which the exciton condensate is enhanced [4].

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Manipulation of band gap upon photoexcitation of an excitonic insulator

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Intriguing goal of time-resolved techniques is to understand and possibly control the ultrafast dynamics of symmetry-broken phases and its application to the excitonic insulators[1]. We will present an example of the dynamical phase transition out of an excitonic insulator phase after photo-excitation using a time-dependent extension of the self-consistent GW method. We connect the evolution of the photoemission spectra to the dynamics of the excitonic order parameter and identify two dynamical phase transition points marked by a slowdown in the relaxation: one critical point is connected with the trapping in a nonthermal state with reduced exciton density and the second corresponds to the thermal phase transition. The transfer of kinetic energy from the photoexcited carriers to the exciton condensate is shown to be the main mechanism for the gap melting. We propose a phenomenological measure for the effective interaction which indicates that screening has minor effects on the low energy dynamics.

In the second part we will explain how the optical excitation can transiently enhance the order parameter, as observed in Ta_2NiSe_5 using time resolved ARPES [3]. By exciting the material above certain critical excitation density the band gap is enhanced, at odds with the expectations for a semiconductor. We show that the order parameter of condensate increases as a result of photoinduced nonthermal electron/hole distribution, screening-induced shifts in the underlying semiconductor band structure and clarify the role of phonons on the enhancement of the order [4].

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Quantum Spectroscopies for quantum materials

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The prospect of "forcing" the formation of quantum coherent states in matter, by means of pulsed electromagnetic fields, discloses a new regime of physics where thermodynamic limits can be bridged and quantum effects can, in principle, appear at ambient temperatures. In this presentation I will introduce the field of optical control of correlated electron systems. I will focus on the possibility of coherently driving low-lying excitations of quantum many body systems making light-based control of quantum phases in real materials feasible. I will show recent results in archetypal strongly correlated cuprate superconductors revealing a Mid-IR driven stabilization of superconducting fluctuations. I will introduce our new approach to go beyond mean photon number observables. I will show that classical and quantum fluctuations of light can provide a richer statistical information than standard linear and non-linear optical spectroscopies.

Characterization of electronic states in κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]I by polarized pump probe spectroscopy

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A series of organic molecular compounds κ -(BEDT-TTF)$_2$Cu[N(CN)$_2$]X (X = Cl, Br and I) has attracted much interest from the viewpoint of fundamental physics and application of devices owing to a rich variety of electronic states which arises from strong electron correlation. The various investigations have revealed that the ground states of X = Cl and Br (κ -Br) salts are the Mott insulator and superconductor, respectively. On the other hand, in X = I (κ-I) salt, the recent resistivity measurements have suggested superconducting and insulating behaviors depending on samples [1]. To characterize the electronic state of κ-I, further measurements are required.

In this study, we carry out the optical pump-probe spectroscopy for two kinds of samples; one is a superconductor (#1) and the other is an insulator (#2), which are characterized by both of X-ray and resistive measurements. By measuring probe polarization dependences of the transient change of reflectivity $\Delta R/R$, we find carrier relaxation dynamics originated from a photoinduced phase separation, fluctuating and bulk superconductivity with T_c of 12 K in #1. These are quite similar to those in the isostructural salt κ -Br [2]. On the other hand, #2 shows a metal-insulator transition at ~ 40 K and, unexpectedly, superconducting transition at T_c ~ 7 K, which have not been observed in other κ -type organic compounds. The distinct difference of carrier dynamics between #1 and #2 indicates that two kinds of electronic states are present in κ -I, leading to the sample-dependent resistive behaviors.

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Y. Nakamura, et. al., The 97th CSJ Annual Meeting, (2017).
[2] S. Tsuchiya et al., Phys. Rev. B 84, 140503 (2017).

Collective states driven far away from the equilibrium

D. Dominko, V. Grigorev, V. Kabanov, J. Demšar

It has been shown that an intense laser pulse can drive a charge density wave (CDW) system far enough to reach a metastable nonthermal state or to melt the low temperature order. While optical pump-probe (P-p) studies show a suppression of the coherent (collective mode) response [1], studies done by a three pulse techniques have revealed various phenomena, from a rapid order parameter recovery [2, 3] to transitions into new states [4,5].

Here, three pulse technique [2] was used to study two systems: $(NbSe_4)_3I$, undergoing pseudo Jahn Teller distortion, and $K_{0.3}MoO_3$, a well studied prototype CDW system. Both systems show no coherent phonon response in the high symmetry state above the phase transition. We used the sequence of three pulses: a strong D-pulse folloved by the P-p sequence [2], where the weak P-p sequence records the real-time collective response as a function of time after the strong D-pulse (t_{12}). For excitation densities (D) comparable to complete quenching of the low-temperature phase, both systems show periodic modulations of strengths (amplitudes) and phases of collective modes as a function of t_{12}, see e.g. Fig. 1. What is particularly interesting is that collective mode amplitudes can be substantially enhanced in the driven state compared to the near-equilibrium case. Moreover, their phases reach values that are not observed in conventional P-p studies.

While some of the observations can be accounted for in terms of existing theoretical models [3,5,6], some, e.g. the nonanalytical dependence of phase on t_{12}, seek for a new theoretical approaches.

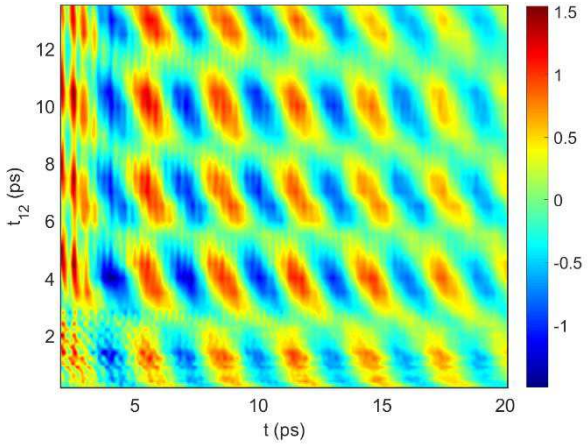

Fig. 1. The oscillatory part of the transients recorded at 5K on $(NbSe_4)_3I$, shown in false color coding as a function of time delay after the strong D-pulse, t_{12}. The time between the pump (P) and probe (p) is denoted by t. The fluence of D pulse was set to 2 mJ/cm^2 and the laser wavelength was 800 nm.

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Ultrafast Spin density wave dynamics at intense optical pulse excitation

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Ultrafast time-resolved spectroscopy has become an important tool for studying rapidly evolving phase transitions because it offers an insight into some microscopic process happening during the transition which can not be observed in equilibrium experiments. Here we will present the ultrafast optical time-resolved spectroscopy measurements of the system trajectory throughaspin density wave (SDW) phase transition in $SrFe_2As_2$ and $EuFe_2As_2$. Using the standard pump-probe technique we estimated the threshold fluence for a nonthermal destruction of the SDW order ($F_{th} \approx 0.3$ mJ/cm^2) at two different pump-photon energies (1.55 eV and 3.1 eV). Using the multi-pulse pump-probe technique the SDW order destruction timescale of ~150 fs was found to be fluence independent. By comparing the temperature dependences of the standard and multi-pulse transient reflectivity long after the arrival of the destruction pulse we determined the transient lattice heating in $SrFe_2As_2$. At high excitation densities (~ mJ/cm^2) the destruction pulse penetration depth significantly exceeds the equilibrium penetration depth suggesting absorption saturation. Using the multipulse pump-probe technique we measured the recovery of the SDW order at different destruction fluences. The fluence of the destruction pulse was used as an adjustable parameter to control the quench conditions [1]. We compared the recovery time of the trajectories to the standard pump-probe transient reflectivity relaxation time measured at similar excitation fluences. In the case of fast quench ($F_D < 2$ mJ/cm^2) the trajectories recover on a sub-ps timescale and the recovery time is faster than the corresponding transient reflectivity relaxation time. The recovery timescales become identical at the crossover from fast to slow quench conditions. In the case of slow quench ($F_D > 2$ mJ/cm^2) the transient reflectivity displays a partial initial fast relaxation with no correspondence in the trajectory dynamics that only shows a slow recovery on a timescale of hundreds of ps.

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Ultrafast Dynamics in Quantum Materials

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Strong correlations between spin, charge, lattice, and orbital degrees of freedom play an important role in the emergent properties of quantum materials. Ultrafast spectroscopies enable the ability to temporally, and recently, spatially, resolve phenomena at the fundamental timescales of atomic and electronic motion. Here, we will review our recent results[1-4] on ultrafast optical studies of spin, charge, and lattice dynamics, and more importantly, of the dynamics of the coupling between these degrees of freedom in a broad range of quantum materials including, magnetic materials, topological materials, and multiferroics.

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Bipolaron mechanism of the organic magnetoresistance as a correlation effect in hopping conduction

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We derive the kinetic equations for the polaron hopping in organics that explicitly take into account the double occupation possibility and pair intersite correlations. The equations provide a comprehensive self-consistent framework for the description of the bipolaron mechanism of the organic magnetoresistance. At low applied voltages the equations can be reduced to effective resistor network that generalizes the Miller-Abrahams network and includes the effect of spin relaxation on the system resistivity. Our approach reveals the close relationship between the organic magnetoresistance and the intersite correlations. In the absence of correlations, as in ordered system with zero Hubbard energy, the magnetoresistance disappears.

Deconstructing anomalous resistivity of bad metals

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Faculty of civil and geodetic engineering, Jamova 2, University of Ljubljana, Slovenia

I will focus on a deconstruction of resistivity on to the charge susceptibility and the diffusion constant and whether it could lead to a better understanding of the anomalous behavior of resistivity in bad-metals. In particular, I will show numerical results obtained by the Finite-temperature Lanczos method for a doped Hubbard model on square and triangular lattice [1], present experimental indications of a distinct behavior and discuss some future challenges.

[1] Jure Kokalj, Phys. Rev. B 95, 041110(R) (2017).

Two unusual CDW systems from the perspective of DFT

J. Mravlje

Jozef Stefan Institute

I will discuss the LDA calculations on two CDW systems TaS_2 and Mo_8O_{23}. Both are characterized by ICDW to CCDW crossover. The former is believed to realize a Mott phase in the CCDW regime. I will describe the DFT results on TaS_2, and relate them to experimental measurements of specific heat, magnetic susceptibility, and NMR. I will discuss the resistivity anisotropy and stress the open question of what blocks the out-of-plane transport.

Mo_8O_{23} also realizes a CDW phase, but in contrast to TaS_2 and many other CDW systems, the host undistorted structure is a semi-metal with a vanishing density of states at the Fermi level and accordingly also vanishing low-energy LDA charge susceptibility, which at first sight precludes nesting scenario. I will argue that the unusual temperature dependence of magnetic susceptibility in this compound that was earlier discussed in terms of the fluctuations of the CDW order parameter is actually due to the semi-metallic DOS. I will discuss a possible scenario for the occurence of the CDW behavior. Within this scenario the ICCDW phase is a high-temperature instability of a semi-conducting low-temperature phase.

Quantum information propagation

David J. Luitz

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I will discuss the transport of information in generic one-dimensional quantum systems using various measures. As a local probe, one can use out-of-time order correlation functions, which quantify the growth of the commutator of local operators in time. They exhibit a light-cone structure in chaotic systems with short range interactions, exhibiting a sublinear envelope in systems with slow dynamics. In long-range interacting spin chains the "light cone" becomes superlinear.

The propagation of information is a generic property of the time evolution operator and therefore also visible in the operator space entanglement entropy of the evolution operator.

Spin dynamics within the block orbital-selective Mott phase

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Iron-based superconductors display a variety of magnetic phases originating in the competition between electronic, orbital, and spin degrees of freedom. Previous theoretical investigations [1] of the one-dimensional (1D) multiorbital Hubbard model revealed the existence of an orbital-selective Mott phase (OSMP) with ferromagnetic or block spin order. In the later, spins of the localized orbital form antiferromagnetically coupled ferromagnetic (FM) islands. Recent inelastic neutron scattering (INS) experiments on quasi-1D $BaFe_2Se_3$ and doped $RbFe_2Se_3$ compounds confirm the relevance of the spin-block phases [2-4]. Moreover, the INS spectrum unveiled exotic features in the dynamical spin structure factor including a low-energy *acoustic* mode and a high-energy *optical* mode. In my talk I present the first theoretical/computational study of the dynamical spin structure factor $S(q,\omega)$ within the block-OSMP using the density-matrix renormalization group method. In agreement with experimental results we find two modes: a dispersive (acoustic) mode for momentum $q < \pi/2$ and a dispersion-less (optical) mode for $q > \pi/2$.

The latter is attributed to local block *Hund excitations*, while the former arises from the dynamics of FM islands.

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[4] M. Mourigal, et al., Phys. Rev. Lett. 115, 047401 (2015).

Correlation functions of the quantum sine-Gordon model: experiment and theory

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The technology of ultra-cold atomic systems has advanced to the level that allows the experimentalists to simulate Hamiltonians of condensed matter models in their laboratories. Recently, the group of Schmiedmayer has published two important articles related to our (theoretical) interest. In the first one, they have experimentally realized an integrable system and demonstrated that it relaxes to a generalized Gibbs ensemble after undergoing a quantum quench. In the second work, they have realized the sine-Gordon model and measured its correlation functions in equilibrium. The first work has come with a very crude theoretical description, the second has been lacking it so far.

The sine-Gordon theory is a paradigmatic model of an interacting quantum field theory which is, among the rest, also attractive because of having quantum analogs of solitons. The direct computation of its correlation functions has so far been out of scope so it is an interesting theoretical question in itself. Very recently, we have succeeded in numerically calculating the sine-Gordon correlation functions - both equilibrium ones and the dynamics following a quench. Thus, we are able to give a theoretical explanation to the experiment and provide some predictions. It seems that we will also be able to provide the theory for the first of the two experiments. In my talk I will give a short overview of the experiments and our theoretical work.

Tuesday, 19 December

	Chair: T. Tohyhama	
9:00 - 9:25	**M. Eckstein**: Theory for the measurement of fluctuations in time-resolved optical spectroscopy	39
9:25 - 9:50	**D. Arcon:** A new high-temperature quantum spin liquid with polaron spins	50
9:50 - 10:15	**I. Žutić**: Magnetic Proximity Effects and Novel Excitation in 2D Materials	41
10:15 - 10:35	*Coffee break*	
	Chair: P. H. M. van Loosdrecht	
10:35 - 11:00	**F. Cliento**: Non-equilibrium dynamics in WTe_2 revealed by optical and photoelectron spectroscopies	42
11:00 - 11:25	**T. Rejec:** Differential thermopower of quantum point contacts	49
11:25 - 11:50	**Z. Papic**: Quantum many-body scars and non-ergodic dynamics in the Fibonacci chain	45
11:50 - 12:05	**L. Ulčakar**: Slow quenches in time-reversal symmetric insulators	46
12:05 - 16:50	*Lunch break*	
	Chair: J. Bonca	
16:50 - 17:15	**T. Tohyama**: Photoinduced absorptions inside the Mott gap in two-dimensional extended Hubbard model	47
17:15 - 17:40	**R. Žitko**: Domain walls in correlated insulators	48
17:40 - 18:05	**V. F. Nasretdinova**: Polarization-resolved transient optical reflectivity studies of the low-symmetry charge-density wave compounds Mo_8O_{23} and Mo_2S_3	43
18:05 - 18:30	**I. Madan**: Light-coupled TEM-Swiss army knife for condensed matter physics	40
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	Chair: A. Taylor	
20:00 - 20:25	**P. H. M. van Loosdrecht**: Ultrafast Raman Scattering in Complex Matter: New Views on Non-Equilibrium Dynamics	51
20:25 - 20:50	**A. Potočnik**: Photon Crystallization in a System of Two NonlinearlyCoupled Superconducting Resonators	52
20:50 - 21:05	**J. Bonca**: Charge vs. Spin Disorder in a Correlated Electron System	53

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Theory for the measurement of fluctuations in time-resolved optical spectroscopy

M. Eckstein

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We show that, in optical pump-probe experiments on bulk samples, the statistical distribution of the intensity of ultrashort light pulses after the interaction with a nonequilibrium complex material can be used to measure the time-dependent noise of the current in the system. We illustrate the general arguments for a photo-excited Peierls material.

The transient noise spectroscopy allows to measure to what extent electronic degrees of freedom dynamically obey the fluctuation-dissipation theorem, and how well they thermalize during the coherent lattice vibrations. The proposed statistical measurement developed here provides a new general framework to retrieve dynamical information on the excited distributions in nonequilibrium experiments which could be extended to other degrees of freedom of magnetic or vibrational origin.

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Light-coupled TEM - Swiss army knife for condensed matter physics

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We will present a brief overview of versatile capabilities of a transmission electron microscope coupled to the ultrafast laser source. In particular, we shall underline some of the projects concluded or in progress in our lab in Lausanne. This will include, time-resolved magnetization dynamics [1]; high energy resolution measurements [2]; high momentum resolution measurements; manipulation of electron wave function; and bringing electron microscopy time-resolution to the level of the optical sources.

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[2] E. Pomarico et al., arXiv:1710.01183 (2017).

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Magnetic Proximity Effects and Novel Excitations in 2D Materials

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Proximity effects can transform a given material through its adjacent regions to become superconducting, magnetic, or topologically nontrivial, enabling emergent phenomena. In bulk materials, the sample size often greatly exceeds the characteristic lengths of proximity effects allowing their neglect. However, in two-dimensional (2D) materials such as graphene or transition-metal dichalcogenides (TMDs), the situation is drastically different, even short-range magnetic proximity effects exceed their thickness and strongly modify spin transport and optical properties [1,2]. The 2D character and reduced screening in TMD lead to the formation of robust excitons with binding energies > 100 meV, orders of magnitude larger than in bulk semiconductors. Focusing on neutral excitons, bound electron-hole pairs that dominate the optical response in TMDs, it is shown that they can provide fingerprints for magnetic proximity effects in magnetic heterostructures [3]. These proximity effects cannot be described by the widely used single-particle description but instead reveal the possibility of a conversion between optically inactive and active excitons by rotating the magnetization of the magnetic substrate. Even in the absence of magnetic substrates, TMDs support formation of novel excitations such as shortwave plasmons paired up with excitons [4]. This coupling elucidates the origin for the optical sideband that is observed repeatedly in monolayers of WSe_2 and WS_2 but not understood. The theory makes it clear why exciton-plasmon coupling has the right conditions to manifest itself distinctly only in the optical spectra of electron-doped W-based TMDs.

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Non-equilibrium dynamics in WTe_2 revealed byoptical and photoelectron spectroscopies

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The interest on the semimetal WTe_2 (tungsten ditelluride) has been recently renewed because of the discovery of interesting properties, such as an extremely large magnetoresistance and possible topological features, under the form of a type-II Weyl phase. Here we combine time-resolved optical and photoelectron spectroscopies to investigate the possibility to control the magnetoresistance of WTe_2 on ultrafast timescales. Time-resolved reflectivity measurements revealed a strongly anisotropic behaviour when probing along the a and b crystallographic directions. The reflectivity variation shows intense coherent features, related to four coherent phonons having ~9 cm^{-1}, ~80 cm^{-1}, ~134 cm^{-1} and ~215 cm^{-1} frequency. The incoherent dynamics relaxes on a ~1 ps timescale, and has been interpreted as a modification of the spectral weight, as corroborated by time and angle resolved photoemission measurements. The photoinduced ultrafast spectral weight modification suggests that a transient imbalance between the density of electrons and holes can be triggered. Since the balance between the densities of electrons and holes is thought to be the prerequisite to achieve an extremely large magnetoresistance, the possibility to transiently alter this perfect compensation points toward the possibility of controlling the magnetoresistance on ultrafast timescales.

I will also present the results of the characterization of a novel HHG beamline that has been developed at the T-ReX Laboratory at the Elettra Synchrotron, that will pave the way to the study of the electron dynamics on correlated and complex materials with high energy/momentum resolutions and low space charge. This is made possible by the high repetition rate operation of the driving laser source, opening the door to the long-sought investigations by TR-ARPES of the entire Fermi surface of materials like copper and iron-based superconductors.

Polarization-resolved transient optical reflectivity studies of the low-symmetry charge-density wave compounds Mo_8O_{23} and Mo_2S_3

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Probe-polarization-selective studies of transient reflectivity by means of pump-probe spectroscopy have been proven useful for the disentangling contribution of the excited modes of different symmetry in strongly correlated systems like cuprates and organic conductors [1-4]. The Raman-tensor formalism developed for description of pump-probe experiments [5] lays ground for understanding of polarization-selective measurements. However, careful analysis is still required in each case to interpret the results, and in case of absorbing media with low symmetry crystal structure such an analysis might be complicated even for static reflectivity and static Raman response [6,7].

Here we present, compare and discuss the results of probe-polarization-resolved transient reflectivity studies of two charge-density-wave (CDW) compounds of a low symmetry: Mo_2S_3 and Mo_8O_{23}. Both compounds develop CDW(s) above room temperature, in monoclinic phase, and experience further lock-in transitions into the state commensurate with lattice, which is triclinic for Mo_2S_3 [8,9]. However the polarization dependencies in the commensurate state are strikingly different. While in case Mo_2S_3 the static and transient reflectivity have essentially the same probe-polarization dependence, weakly depending on the temperature, in case of Mo_8O_{23} this is not true. Probe-polarization dependence of transient reflectivity of Mo_8O_{23} strongly evolves with temperature, yielding very special tangent-like shape of polarization dependence of normalized reflectivity in the commensurate state.

We argue that the reason for such a difference is the absence of inversion symmetry in the commensurate state of Mo_8O_{23} and preservation of inversion symmetry in the commensurate state of Mo_2S_3, revealed by structural studies [8,9]. We suggest an absence of the inversion symmetry yields the contribution from previously forbidden infrared modes in the pump-probe response as it have been proposed in [10]. We discuss possible impacts of structural changes on the probe-polarization dependence of transient reflectivity.

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Quantum many-body scars and non-ergodic dynamics in the Fibonacci chain

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Recent experiments on large chains of Rydberg atoms [H. Bernien et al., arXiv:1707.04344] have demonstrated the possibility of realizing 1D systems with locally constrained Hilbert spaces, along with some surprising signatures of non-ergodic dynamics, e.g., persistent oscillations following a quench from the Neel product state. I will argue that this phenomenon is a manifestation of a "quantum many-body scar", i.e., a concentration of extensively many eigenstates of the system around special many-body states. The special states are analogs of classical periodic orbits in the single-particle quantum scars. I will present a model based on a single particle hopping on the Hilbert space graph, which quantitatively captures the scarred wave functions up to large systems of 32 atoms. Our results suggest that scarred many-body bands give rise to a new universality class of quantum dynamics, which opens up opportunities for creating and manipulating novel states with long-lived coherence in systems that are now amenable to experimental study.

Slow quenches in time-reversal symmetric insulators

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We study slow quenches between different topological regimes of the two dimensional time-reversal symmetric topological systems, described by the BHZ model. When time-dependent Hamiltonian is time-reversal symmetric, the topological phase is protected by the gap closing and the system ends up in a state far from equilibrium. The Z_2 invariant stays unchanged under symmetry preserving unitary evolution. Interestingly, the time-averaged non-equilibrium bulk spin Hall conductivity approaches the topological equilibrium value in the limit of infinitely slow quench. We also consider slow quenches in models where we break the time-reversal symmetry in a way which keeps the bulk gap opened at all times. In this case the Z_2 invariant changes to the new equilibrium value. We explore to what extent the spin Hall conductivity is different from the time-reversal symmetric one.

Photoinduced absorptions inside the Mott gap in the two-dimensional extended Hubbard model

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Pump-probe spectroscopy is a good tool to characterize electronic states in strongly correlated electron systems. One of the examples is pump-probe optical measurements in the two-dimensional (2D) Mott insulators, La_2CuO_4 and Nd_2CuO_4. Photoinduced midgap excitations inside the Mott gap have been reported just after pumping [1]. The excitations at midinfrared region have been assigned to those due to photoinduced holons and doublons through the comparison with absorption spectra in $La_{2-x}Sr_xCuO_4$ and $Nd_{2-x}Ce_2CuO_4$. On the other hand, photoinduced excitations just below the Mott gap have been attributed to thermalization effects, consistent with thermal broadening of absorption spectra [1]. Even for hole-doped cuprates, similar pump-probe experiments have been done and the emergence of spectral weight just below Mott-gap excitations has been reported [2].

We theoretically investigate pump-probe optical responses in the 2D extended Hubbard model describing cuprates by using a time-dependent Lanczos method [3]. At half filling, pumping generates photoinduced absorptions inside the Mott gap. A part of low-energy absorptions is attributed to the independent propagation of photoinduced holons and doublons. The spectral weight just below the Mott gap increases with decreasing the on-site Coulomb interaction U. We find that the next-nearest-neighbor Coulomb interaction V_1 enhances this U dependence, indicating the presence of biexcitonic contributions formed by two holon-doublon pairs. This result clearly indicates that the enhancement of spectral weight below the Mott gap after pumping is not only due to the temperature effect as suggested by the experiment [1] but also the presence of biexcitons. Photopumping in hole-doped systems also induces spectral weights below remnant Mott-gap excitations, being consistent with recent experiments [2]. The induced weights are less sensitive to V_1 and may be related to the formation of a biexcitonic state in the presence of hole carriers.

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Domain walls in correlated insulators

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The spectral gap of insulating strongly correlated materials with periodic lattice deformation may be a simple band gap or a correlation-induced Mott gap. The defects in the lattice deformation (e.g. a domain wall between two charge-density-wave domains) may give rise to in-gap states that are spatially localized close to the defect structure. I will discuss two aspects of this problem:

1) In the Su-Schrieffer-Heeger model of a dimerized tight-binding chain, a topologically protected electronic state appears at the Fermi level at the interface between two topologically different domains. This state persists in the presence of an on-site (Hubbard) interaction, but moves away from the Fermi level. The simple extension of the SSH model to period-3 deformation has a Mott gap rather than a band gap. Do we expect topological in-gap states in this case, too?

2) Moving two half-planes of triangular lattice closer together results in enhanced hopping along a one-dimensional zig-zag chain of domain-wall atoms. Can this system metallize through a bandwidth-driven Mott metal-insulator transition? What is the nature of the ensuing metallic state (it is unlikely to be a Fermi liquid, given that it is a 1D metal embedded in a 2D system with ungapped spin fluctuations)?

Differential thermopower of quantum point contacts

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Quantum point contacts (QPCs) are basic building blocks of mesoscopic devices. Their conductance is quantized, i.e it is a product of the conductance quantum and the number of open channels. An additional feature named the "0.7 anomaly" has been observed in QPCs, whose origin has been a subject of intensive discussion in the last couple of decades. In the past we have attributed this anomaly to the emergence of a quasi-bound state at the QPC. In this talk I will describe a new experiment which measured the differential thermopower through a QPC and present density functional theory calculations which explain many of the features observed in the experiment.

An unconventional quantum spin liquid with atomic-cluster spins in 1T – TaS_2

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The existence of a quantum spin liquid (QSL) in which quantum uctuations of spins are sufficiently strong to preclude spin ordering down to zero temperature was originally proposed theoretically more than 40 years ago, but its experimental realisation turned out to be very elusive. In 1973 Anderson introduced a resonating valence bond (RVB) state [1] as a new kind of insulator that was proposed to be the ground state of the triangular-lattice S = 1/2 Heisenberg antiferromagnet instead of a more conventional Néel state. The proposal was put forward to account for the unusual magnetic properties of a perfect triangular atomic lattice of Ta atoms in the layered transition metal dichalcogenide 1T-TaS_2. Since then, the list of materials with triangular lattice and with properties indicating the existence of QSL, i.e., a state without spontaneously broken triangular lattice symmetry and whose behaviour is dominated by emergent fractional excitations, is still remarkably short: it includes $YbMgGaO_4$[2] and some organic molecular solids, e.g., κ-$(ET)Cu_2(CN)_3$ [3]. Compared to these compounds, layered dichalcogenides have perfect triangular lattice geometry and a weaker spin-orbit coupling, offering a possibility for obtaining a unique insight into the competition between antagonistic QSL and Néel state, however, no signatures of QSL behaviour have been observed so far with spins on atomic lattice sites. Here we report [4] on an almost ideal QSL that appears to be realized by atomic-cluster spins on the triangular lattice of a charge-density wave (CDW) state of 1T-TaS. In this system, the charge excitations have a well-de_ned gap of about ~ 0.3 eV, while nuclear magnetic quadrupole resonance and muon spin relaxation experiments reveal that the spins show gapless quantum spin liquid dynamics and no long range magnetic order down to 70 mK. Canonical T^2 power-law temperature dependence of the spin relaxation dynamics characteristic of a QSL is observed from 200 K to T_f = 55 K. Below this temperature we observe a new gapless state with reduced density of spin excitations and high degree of local disorder signifying new quantum spin order emerging from the QSL.

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Ultrafast Raman Scattering in Complex Matter: New Views onNon-Equilibrium Dynamics

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Many materials show fascinating physical phenomena when brought out of their normal thermal equilibrium state. For strongly perturbed systems, these phenomena include, among other, transitions into non-thermal states of matter and ultrafast switching of order parameters like magnetization. Closer to equilibrium, non-thermal states can provide a unique insight into the dynamical behavior of the various degrees of freedom (charge, lattice, spin, orbital occupation) in a material, and into the coupling between them. In this colloquium I will introduce a less common technique to study non-equilibrium state: ultrafast Raman scattering. It's potential and unique properties will be discussed by highlighting some recent results, including the observation of a transient Fano resonance in silicon, a study of exciton dynamics in graphene nano-ribbons, and experiments on ultrafast energy and momentum transfer between magnons and phonons in a skyrmionic material.

Photon Crystallization in a System of Two Nonlinearly Coupled Superconducting Resonators

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Multi-site systems with strong inter-site photon-photon interactions can exhibit spatial modulation of photon density known as the photon crystalline phase [1]. We have engineered such system with a SQUID-mediated nonlinear coupling between two superconducting on-chip resonators in the microwave frequency domain [2]. In this circuit QED implementation, we employ lumped-element type resonators, which consist of Nb thin film structured into interdigitated finger shunt capacitors and meander inductors. By strongly detuning the resonance frequencies of the two resonators and introducing ac magnetic flux modulation through the SQUID loop we obtain a system that is governed by an effective Hamiltonian containing strong on-site Kerr (U) and cross Kerr (V) interaction terms as well as a tunable linear hopping (J) term. We fully characterize our system by performing spectroscopic measurements in a dilution refrigerator at 20 mK. Driving both non-linear resonators at the ground-to-excited state transition frequencies simultaneously we measure second-order correlation function of photons emitted from the cavities. For vanishing exchange interaction (J) we observe both on-site and inter-site anti-bunching of photons, which is a signature of the photon crystalline phase. By increasing exchange interaction we destroy anti-bunching and move towards the uniform phase. To the best of our knowledge this is the first experimental demonstration of the photon crystalline phase induced by the cross-Kerr interaction. Our experiment presents an elementary building block that can serve as a precursor for more complex geometries and thus pave the way to a number of novel quantum phases of light in a driven-dissipative system [1].

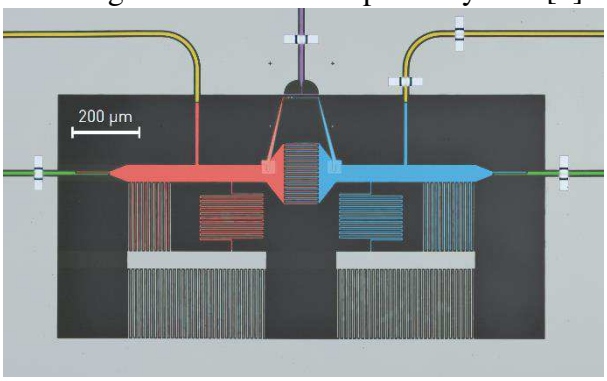

Fig.1: False-colored micrograph of two lumped-element cavities coupled via an interdigitated capacitor and a SQUID.

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Charge vs. Spin Disorder in a Correlated Electron System

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In the first part [1] I will show that electron-magnon interaction delocalizes the particle in a system with strong charge disorder. The analysis is based on results obtained for a single hole in the one–dimensional t–J model. Unless there exists a mechanism that localizes spin excitations, the charge carrier remains delocalized even for a very strong charge disorder and shows subdiffusive motion up to the longest accessible times.

In the second part [2] I will present a study of dynamics of a single hole in one dimensional t–J model subject to a random magnetic field. Strong disorder that couples only to the spin sector localizes both spin and charge degrees of freedom. While we cannot precisely pinpoint the threshold disorder, we conjecture that there are two distinct transitions. Weaker disorder first causes localization in the spin sector. Carriers become localized for somewhat stronger disorder, when the spin localization length is of the order of a single lattice spacing. I will also discuss finite doping.

[1] J. Bonca and M. Mierzejewski, *Phy. Rev. B* **95**, 214201 (2017).
[2] G. Lemut, M. Mierzejewski, and J. Bonca, arXiv:1711.10956, Accepted for publication in *Phys. Rev. Lett.*

On diffusion in integrable systems

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Out-of-equilibrium properties are one of the central interests in the study of many-body systems. As a consequence of local conservation laws, integrable systems typically exhibit ballistic transport. However, in certain cases appropriate conservation laws might be absent, raising the question about the nature of the transport.

In my talk I will present two results on the topic. The first one establishes the connection between the diffusion constant and the ideal transport coeficient, the Drude weight. This result is used to calculate the lower bound on diffusion constant in anisotropic Heisenberg model.

In the second part I will deal with the classical deterministic cellular automaton, describing the dynamics of charged, hard-core interacting particles. Besides the ballistic and insulating regime, the model, surprisingly, exhibits diffusive transport for certain values of parameters. The toy model offers the insight in possible generic mechanism behind the diffusion in integrable systems, which can be viewed as an interplay between the insulating behavior of charged particles and the ballistic nature of neutral degrees of freedom.

[1] M. Medenjak, C. Karrasch, and T. Prosen, Phys. Rev. Lett. 119, 080602 (2017).
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Wednesday, 20 December

	Chair: P. Prelovšek	
9:00 - 9:25	**T. Prosen**: Many-body quantum chaos: The first analytic connection to random matrix theory	57
9:25 - 9:50	**S. Sotiriadis**: Quantum Transport after Inhomogeneous Quenches	58
9:50 - 10:15	**Z. Lenarčič**: Time-dependent generalized Gibbs ensembles in open systems	59
10:15 - 10:45	*Coffee break*	
	Chair: F. Heidrich-Meisner	
10:45 - 11:10	**B. Bertini:** Transport in Closed One-Dimensional Systems: Integrable Models and Universality at Low Temperatures	60
11:10 - 11:25	**D. Brecht**: Analysis of the Temperature Behaviour of a QubitCalorimeter model	61
11:25-11:40	*Closing*	

Many-body quantum chaos: The first analytic connection to random matrix theory

T. Prosen

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A key goal of quantum chaos is to establish a relationship between widely observed universal spectral fluctuations of clean quantum systems and random matrix theory (RMT). For single particle systems with fully chaotic classical counterparts, the problem has been partly solved by Berry (1985) within the so-called diagonal approximation of semiclassical periodic-orbit sums.

Derivation of the full RMT spectral form factor K(t) from semiclassics has been completed only much later in a tour de force by Mueller et al (2004). In recent years, the questions of long-time dynamics at high energies, for which the full many-body energy spectrum becomes relevant, are coming at the forefront even for simple many-body quantum systems, such as locally interacting spin chains. Such systems display two universal types of behaviour which are termed as 'many-body localized phase' and 'ergodic phase'. In the ergodic phase, the spectral fluctuations are excellently described by RMT, even for very simple interactions and in the absence of any external source of disorder. In my talk I will outline the first theoretical explanation for these observations. I will show how to compute K(t) explicitly in the leading two orders in t and show its agreement with RMT for non-integrable, time-reversal invariant many-body systems without classical counterparts, a generic example of which are Ising spin 1/2 models in a periodically kicking transverse field.

Quantum Transport after Inhomogeneous Quenches

S. Sotiriadis[1]

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I will discuss quantum dynamics and transport in systems that are initially split in two halves lying at different temperature or particle density and abruptly connected. After such an inhomogeneous quench, a Non-Equilibrium Steady State (NESS) typically forms in the thermodynamic and large time limit. I will demonstrate how the emergence of NESS can be derived from first principles, starting from non-interacting lattice models in one dimension and considering the effects of different boundary conditions and of interacting defects. Next I will focus on a genuinely interacting integrable system, the Lieb-Liniger gas, for which it has been recently conjectured that Generalised Hydrodynamics (GHD) emerges at large times. I will derive an exact determinant formula for the NESS and show how certain predictions of the above conjecture can be deduced from it.

Parts of this work in collaboration with: M. Ljubotina, T. Prosen (Univ. of Ljubljana) and A. Giuliani (Univ. of Roma Tre).

Time-dependent generalized Gibbs ensembles in open systems

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The concept of generalized Gibbs ensembles intrigued the 'nonequilibrium' community for a few years, bearing a great conceptual significance but also some controversy. Despite all that, already its truncated version typically proved sufficient for calculations of local observables in the steady state reached after a quantum quench in an integrable model. Recently we showed [1] that it can also be used as an approximate thermodynamic description for steady states of nearly integrable quantum systems that are weakly open and weakly driven.

In the talk I will argue that after the systems has prethermalized to the GGE manifold, time-dependent Lagrange parameters can capture also the slow approach to the steady state of weakly open and driven system. I will present our results on the Heisenberg spin chain in the presence of weak Lindblad perturbations, a setup possibly realized in quantum optics or trapped ions experiments. Same approach can also be used in condensed matter systems, for example to determine the slow time-dependence of temperature and chemical potentials for systems that are approximately described by open Boltzmann dynamics [2].

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[2] Z. Lenarčič, F. Lange, A Rosch, arXiv:1706.05700 (2017).

Transport in Closed One-Dimensional Systems: Integrable Models and Universality at Low Temperatures

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I consider a general framework for studying transport problems in closed systems. Two semi-infinite halves at different temperatures and magnetisations are suddenly joined together and then left to evolve unitarily. In the integrable case, at large times, the system can be locally represented by a family of space- and time-dependent stationary states, which are fully characterised by a set hydrodynamic equations. I illustrate this theory focusing on the prototypical case of the XXZ spin-1/2 chain, and presenting several results obtained recently. I show how the general hydrodynamic equations can account for a rich phenomenology depending on the specific choice of the systems's parameters, including the emergence of high-temperature sub-ballistic behaviour. Moreover, some universal features in the transport dynamics emerge at low temperatures irrespectively of integrability. Here I focus on a universal broadening of the light cone due to non-conformal corrections which is predicted by means of a non-linear Luttinger liquid theory. In integrable models this prediction is analytically confirmed by the hydrodynamic approach.

Analysis of the Temperature Behaviour of a Qubit-Calorimeter model

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We model and study the qubit-calorimeter setup proposed by [1] for periodic driving. The calorimeter is a finite-sized thermal electron bath. We exploit the periodicity of the drive to derive two coupled stochastic jump processes, one for the state of the qubit and another for the temperature of the calorimeter. We consider an additional electron-phonon interaction, which adds a drift and noise to the evolution of the temperature. Via numerical and analytic methods, we study the temperature behaviour of the qubit calorimeter setup on two timescales. On the shorter timescale, the temperature only makes a few jumps. Instead, for longer times the temperature performs many jumps and reaches a steady state. On this timescale, we use multiscale perturbation theory to reduce the coupled qubit-temperature process to an effective temperature process. The effective process allows us to predict the steady state distribution of the temperature and the relaxation time to said steady state. The analytic results correspond well with the numerics.

[1] J. Pekola, P. Solinas, A. Shnirman, and D. V. Averin, *New. J. phys.* **15**, 115006 (2013).

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PROGRAMME

Sunday, 17. 12. 2017	
12:00 – 14:00	*Registration*
14:00 – 14:15	*Opening*
	Chair: Demsar
14:15 – 14:40	Parmigiani
14:40 – 15:05	Mihailovic
15:05 – 15:30	Gerasimenko
15:30 – 15:55	Karpov
15:55 – 16:10	Ravnik
16:10 – 16:25	Vodeb
16:25 – 16:50	*Coffe Break*
	Chair: Parmigiani
16:50 – 17:15	Kimel
17:15 – 17:40	Demšar
17:40 – 18:05	Pogrebna
18:05 – 18:30	Ligges
18:30 – 20:00	*Dinner break*
	Chair: Kabanov
20:00 – 20:25	Heidrich-Meisner
20:25 – 20:50	Prelovšek
20:50 – 21:05	Zadnik

Monday, 18. 12. 2017	
	Chair: Kimel
9:00 – 9:25	Perfetti
9:25 – 9:50	Monney
9:50 – 10:15	Golež
10:15 – 10:35	*Coffee break*
	Chair: Perfetti
10:35 – 11:00	Fausti
11:00 – 11:25	Tsuchiya
11:25 – 11:50	Dominko
11:50 – 12:05	Naseska
12:05 – 16:50	*Lunch break*
	Chair: Lenarčič
16:50 – 17:15	Taylor
17:15 – 17:40	Kabanov
17:40 – 18:05	Kokalj
18:05 – 18:30	Mravlje
18:30 – 20:00	*Dinner break*
	Chair: Trugman
20:00 – 20:25	Luitz
20:25 – 20:50	Herbrych
20:50 – 21:05	Kukuljan
21:15	*Social event*

Tuesday, 19. 12. 2017	
	Chair: Tohyama
9:00 – 9:25	Eckstein
9:25 – 9:50	Arčon
9:50 – 10:15	Žutić
10:15 – 10:35	*Coffee break*
	Chair: van Loosdrecht
10:35 – 11:00	Cilento
11:00 – 11:25	Rejec
11:25 – 11:50	Papič
11:50 – 12:05	Ulčakar
12:05 – 16:50	*Lunch break*
	Chair: Bonca
16:50 – 17:15	Tohyama
17:15 – 17:40	Žitko
17:40 – 18:05	Nasretdinova
18:05 - 18:30	Madan
18:30 – 20:00	*Dinner break*
	Chair: Taylor
20:00 – 20:25	van Loosdrecht
20:25 – 20:50	Potočnik
20:50 – 21:15	Bonča
21: 15 – 21:30	Medenjak

Wednesday, 20. 12. 2017	
	Chair: Prelovšek
9:00 – 9:25	Prosen
9:25 – 9:50	Sotiriadis
9:50 – 10:15	Lenarčič
10:15 – 10:45	*Coffee break*
	Chair: H.-Meisner
10:45 – 11:10	Bertini
11:10 – 11:25	Brecht
11:25 – 11:40	*Closing*