

Nonequilibrium Phenomena in Complex Matter: new observations and new theories

BOOK OF ABSTRACTS



Ambrož, Krvavec, Slovenia, 13-16 December 2015

PROGRAMME

Sunday, 13. 12. 2015

13:00 - 15:45	Arrival & Registration
15:45 - 16:00	Opening
	Chair: Werner
16:00 - 16:30	Fausti
16:30 - 17:00	Tohyama
17:00 - 17:20	<i>Coffe Break</i>
	Chair: Eckstein
17:20 - 17:50	Zlatič
17:50 - 18:20	Kogoj
18:20 - 20:00	<i>Dinner break</i>
	Chair: Kabanov
20:00 - 20:30	Pogrebna
20:30 - 21:00	Medvedyeva

Monday, 14. 12. 2015

	Chair: Mihailovic
9:00 - 9:30	Ligges
9:30 - 10:00	Prelovšek
10:00 - 10:20	<i>Coffee break</i>
	Chair: Bonca
10:20 - 10:50	Prosen
10:50 - 11:20	Vaskivskiyi
11:20 - 11:50	Mierzejewski
11:50 - 16:50	<i>Lunch break</i>
	Chair: Trugman
16:50 - 17:20	Werner
17:20 - 17:50	Žitko
17:50 - 18:20	Subhankulov
18:20 - 20:00	<i>Dinner break</i>
	Chair: Golež
20:00 - 20:30	Kabanov
20:30 - 21:00	Madan

Tuesday, 15. 12. 2015

	Chair: Tohyama
9:00 - 9:30	Cilento
9:30 - 10:00	Mihailovic
10:00 - 10:20	<i>Coffee break</i>
	Chair: Prosen
10:20 - 10:50	Eckstein
10:50 - 11:20	Baldini
11:20 - 11:50	Ramšak
11:50 - 16:50	<i>Lunch break</i>
	Chair: Prelovsek
16:50 - 17:20	Miyajima
17:20 - 17:50	Borzda
17:50 - 18:20	Vega-Mayoral
18:20 - 20:00	<i>Dinner break</i>
	Chair: Pogrebna
20:00 - 20:30	Gadermeier
20:30 - 21:00	Gerasimenko
21:00 - 21:30	Vella

Wednesday, 16. 12. 2015

	Chair: Ligges
9:00 - 9:30	Nasretdinova
9:30 - 10:00	Borovšak
10:00 - 10:20	<i>Coffee break</i>
	Chair: Mierzejewski
10:20 - 10:50	Golež
10:50 - 11:20	Chudzinski
11:20 - 11:50	Medenjak
11:50 - 12:05	Closing

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Matter: new observations and new theories**

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Nonequilibrium Phenomena in Complex Matter: new observations and new theories

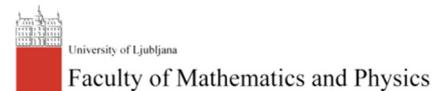
December 13 - 16, 2015
Ambrož, Krvavec, Slovenia

Organized by:

Jožef Stefan Institute, Ljubljana, Slovenia



Faculty for Mathematics and Physics,
University of Ljubljana, Slovenia



Center of Excellence in Nanoscience and Nanotechnology,
Ljubljana, Slovenia



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CONTENT

Programme	5
Abstracts.....	9
List of participants.....	52

Programme

Sunday, 13 December

13:00 - 15:45	Arrival & Registration	
15:45 - 16:00	Opening	
	Chair: Werner	
16:00 - 16:30	Fausti: Disclosing fluctuations of lattice atomic positions by non-equilibrium optical experiments	11
16:30 - 17:00	Tohyama: Optical conductivity out of equilibrium in strongly correlated electron systems	12
	Chair: Eckstein	
17:20 - 17:50	Zlatič: Nonlinear Peltier effect and the nonequilibrium Jonson-Mahan theorem	13
17:50 - 18:20	Kogoj: Thermalization after photoexcitation from the perspective of optical spectroscopy	14
	Chair: Kabanov	
20:00 - 20:30	Pogrebna: Superconducting gap in $\text{BaFe}_2(\text{As}_{1-x}\text{Px})_2$ from temperature-dependent transient optical reflectivity	16
20:30 - 21:00	Medvedyeva: Many-body localization in open systems	17

Monday, 14 December

	Chair: Mihailovic	
9:00 - 9:30	Ligges: Ultrafast response of the Mott insulator $1T\text{-TaS}_2$	18
9:30 - 10:00	Prelovšek: Can charge-density waves and Mott cooperate?	19
	Chair: Bonca	
10:20 - 10:50	Prosen: Exactly solvable cellular automaton model of steady state non-equilibrium transport	20
10:50 - 11:20	Vaskivskiy: Properties of the hidden quantum state in $1T\text{-TaS}_2$	21
11:20 - 11:50	Mierzejewski: Conserved quantities in integrable and perturbed integrable models	22
	Chair: Trugman	
16:50 - 17:20	Werner: Towards an ab-initio simulation of nonequilibrium phenomena in correlated materials	23
17:20 - 17:50	Žitko: Sub-gap states in the Anderson impurity model at finite temperature and spectroscopy at finite bias voltage	24
17:50 - 18:20	Subhankulov: Ultrafast modulation of magneto-optical Faraday effect	25
	Chair: Golez	
20:00 - 20:30	Kabanov: Dynamics of resistive state in thin superconducting channels	27
20:30 - 21:00	Madan: Optically assisted switching between phase slip configurations in superconducting nanowires	28

Tuesday, 15 December

	Chair: Tohyama	
9:00 - 9:30	Cilento: Time-resolved XUV photoemission: a new clue for understanding the ultrafast dynamics in copper oxides	29
9:30 - 10:00	Mihailovic: How rapidly do ordered states form in cuprates?	30
	Chair: Prosen	
10:20 - 10:50	Eckstein: How fast does the quasiparticle band emerge in a strongly correlated metal?	31
10:50 - 11:20	Baldini: Evidence for Pre-Formed Cooper Pairs in the Pseudogap Phase of Slightly Underdoped $\text{NdBa}_2\text{Cu}_3\text{O}_{6+x}$	32
11:20 - 11:50	Ramšak: Exact non-adiabatic qubit manipulation on Rashba rings	34
	Chair: Prelovsek	
16:50 - 17:20	Miyajima: Superfluorescence of CuCl Quantum Dots Assembly	35
17:20 - 17:50	Borzda: Charge photogeneration in few-layer MoS_2	37
17:50 - 18:20	Vega-Mayoral: Exciton and charge carrier dynamics in few-layer WS_2 and dynamics thickness dependence in MoS_2 few-layer selection	39
	Chair: Pogrebna	
20:00 - 20:30	Gadermeier: Photoinduced Charge Transfer between MoS_2 and organic semiconductors	41
20:30 - 21:00	Gerasimenko: Emergence of soliton phase in Q1D organic conductors as evidenced by nonlinear transport	43
21:00 - 21:30	Vella: Field Induced dissociation of Excitons in MoS_2 monolayer	44

Wednesday, 16 December

	Chair: Ligges	
9:00 - 9:30	Nasretdinova: Light-induced transition from hard to soft gap in CDW conductor NbS ₃ (phase II) at 77 K	46
9:30 - 10:00	Borovšak: Femtosecond relaxation dynamics in CDW molybdenum oxides η -Mo ₄ O ₁₁ and Mo ₈ O ₂₃	48
	Chair: Mierzejewski	
10:20 - 10:50	Golež: Relaxation dynamics of the excitonic insulator	49
10:50 - 11:20	Chudzinski: Exact solutions for finite time quench protocols in Tomonaga-Luttinger liquids: from sudden quench to pumping	50
11:20 - 11:50	Medenjak: Quasilocal conserved quantities in isotropic Heisenberg spin chain	51
11:50 - 12:05	Closing	

Abstracts

Disclosing fluctuations of lattice atomic positions by non-equilibrium optical experiments

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Fluctuations of the atomic positions are at the core of a large class of unusual material properties ranging from quantum para-electricity and charge density wave to, possibly, high temperature superconductivity. Their measurement in solids is subject of an intense scientific debate focused on the research of a methodology capable of establishing a direct link between the variance of the ionic displacements and experimentally measurable observables. In this presentation I will introduce our new approach to address fluctuation by means of non-equilibrium optical experiments performed in shot-noise limited regime. The variance of the time dependent atomic positions and momenta is directly mapped into the quantum fluctuations of the photon number of the scattered probing light. A fully quantum description of the non-linear interactions between photonic and phononic fields pave the way for a direct measurement of fluctuation in complex systems.

References:

- [1] Nature Comm. 5, 5112 (2014)
- [2] New J. Phys. 16 043004 (2014)

Optical conductivity out of equilibrium in strongly correlated electron systems

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A numerical method to calculate optical conductivity based on a pump-probe setup is discussed [1]. Its validity and limits are demonstrated via the numerical simulations on the half-filled one-dimensional extended Hubbard model both in equilibrium and out of equilibrium. By employing either a step-like or a Gaussian-like probing vector potential, it is found that in nonequilibrium, the method can be related to the linear response theory [2] or a different generalized Kubo formula [3], respectively. The observation reveals the probe-pulse dependence of the optical conductivity in nonequilibrium, which may have its applications in the theoretical analysis of ultrafast spectroscopy measurements. The numerical method is applied to nonequilibrium optical responses in the various phases (spin-density wave, charge-density wave, and single-superconducting phases) of the half-filled one-dimensional extended Hubbard model [4,5].

References:

- [1] C. Shao, T. Tohyama, H.-G. Luo, and H. Lu, arXiv:1507.01200.
- [2] Z. Lenarcic, D. Golez, J. Bonca, and P. Prelovsek, Phys. Rev. B **89**, 125123 (2014).
- [3] G. De Filippis, V. Cataudella, E. A. Nowadnick, T. P. Devereaux, A. S. Mishchenko, and N. Nagaosa, Phys. Rev. Lett. **109**, 176402 (2012).
- [4] H. Lu, C. Shao, J. Bonca, D. Manske, and T. Tohyama, Phys. Rev. B **91**, 245117 (2015).
- [5] N. Bittner, T. Tohyama, D. Manske, in preparation

Nonlinear Peltier effect and the nonequilibrium Jonson-Mahan theorem

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We study the energy currents of many body systems in the nonlinear/nonequilibrium regime corresponding to large amplitude (spatially uniform but time-dependent) electric fields. Using the vector gauge and Peierls substitution, we find a relationship between the expectation values for the charge current and for the energy current that reduces to the Jonson-Mahan theorem in the linear-response regime. The formalism holds for arbitrary many-body systems with local interactions. We illustrate it for the Falicov-Kimball, Hubbard, and periodic Anderson models. For noninteracting electrons propagating on a d-dimensional hypercubic lattice in the presence of the vector potential oriented along the main $(1, 1, 1, \dots)$ diagonal, we find that the charge and energy currents exhibit Bloch oscillations. For interacting electrons, described by the the Falcov-Kimball model, we show the preliminary results for the ratio of the charge and energy currents.

Thermalization after photoexcitation from the perspective of optical spectroscopy

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We analyze thermalization after the primary relaxation process of a photoexcited charge carrier coupled to quantum Einstein phonons. If the carrier excitation is sufficiently strong, the system relaxes after the primary energy redistribution towards a steady state. Then, the one-particle density matrix relevant for charge degrees of freedom along with the time-resolved optical conductivity take the form of their thermal counterparts. Our results indicate that steady states are thermal and the temperature can be read out from the optical conductivity. Therefore, secondary relaxation processes observed in time-resolved ultrafast spectroscopy can be efficiently described by applying (quasi)thermal approaches, e.g., multi-temperature models.

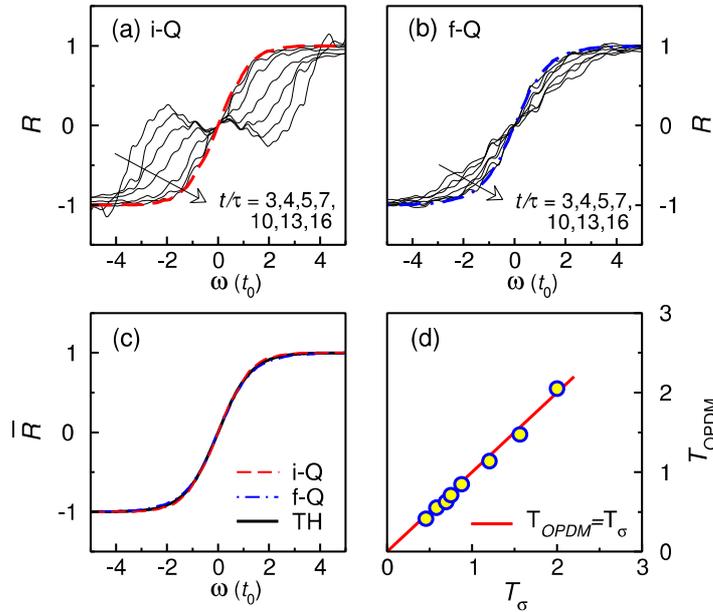


Figure: (a) and (b): Time evolution of a dynamical correlation function connected to optical conductivity, displayed at different times, for two different quench protocols leading to the same total energy. (c) Comparison of time averaged dynamical correlation functions with the thermal form. (d) Comparison of temperatures obtained from the Gibbs state using FTLM and extracted

from the nonequilibrium response for systems with matching kinetic energy.

References:

- [1] J. Kogoj, L. Vidmar, M. Mierzejewski, S. A. Trugman, and J. Bonca, Thermalization after photoexcitation from the perspective of optical spectroscopy, arXiv:1509.08431

Superconducting gap in $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ from temperature-dependent transient optical reflectivity

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We report on ultrafast optical reflectivity measurements of the superconducting gap in optimally doped $\text{BaFe}_2(\text{As}_{0.7}\text{P}_{0.3})_2$ iron pnictide. Isovalently doped $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ stands out from other iron pnictides due to the presence of nodes in superconducting gap, which can influence photoexcited quasiparticle relaxation.

Temperature and fluence dependence of the 1.55-eV optical transient reflectivity was measured and analyzed in the low and high excitation density limit. The effective magnitude of the superconducting gap of ~ 5 meV obtained from the low-fluence-data bottleneck model fit is consistent with the angle-resolved photoemission spectroscopy results for the - and -hole Fermi surfaces.

The superconducting state non-thermal optical destruction energy was determined from the fluence dependent data. The planar optical destruction energy density scales well with T_c^2 and is found to be similar in a number of different layered superconductors, which suggests no influence of nodes on the relaxation dynamics.

Many-body localization in open systems

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We consider a typical strongly interacting disordered system (XXZ spin 1/2 chain in random magnetic field) whose dynamics exhibits localization behavior, which is seen from the presence of the local integrals of motion and the slow growth of entanglement entropy. When coupled to the bath, on time scales smaller than the bath coupling the system still preserves its localized nature, with eigenstates broadened by the interaction with the bath. In the presence of particle exchange with the bath the relaxation to the non-equilibrium steady state (NESS) is exponentially fast, whereas with dephasing noise only the relaxation to the NESS is slower. Surprisingly, the slow relaxation is not directly related to the initial many-body localized nature of the system and is described by a classical diffusion process in the many-particle basis.

Ultrafast response of the Mott insulator 1T-TaS₂

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Using femtosecond time resolved photoemission spectroscopy we study the photo-induced excitation of the prototypical Mott insulator 1T-TaS₂. An unoccupied electronic state is observed in the correlated commensurate and nearly-commensurate CDW phases of the material that is found to be absent in the (nearly) metallic incommensurate CDW phase. From its energetic position ($E-E_F = +170$ meV) this state might be identified as the upper Hubbard. The population dynamics of this spectrally coherent signature follows the temporal laser pulse profile and can be clearly separated from the underlying incoherent electronic population dynamics that show a life time of $\tau \approx 250$ fs. While the signature intensity scales linear with excitation fluence, the optimum spectroscopic contrast is achieved for rather weak pumping ($F < 100$ $\mu\text{J}/\text{cm}^2$, $\hbar\omega = 1.5$ eV). The intensity contrast quickly diminishes for higher excitation fluences up to $F \approx 2000$ $\mu\text{J}/\text{cm}^2$ due to an increase in spectrally incoherent contributions, caused by secondary excitations. Previous studies observed electronic excitations in the same energetic range and assigned them as midgap resonances [1] or polaronic excitations [2]. We conclude that this state is the upper Hubbard band that directly reflects the almost unperturbed presence of charge order in the system which promptly collapses after a certain amount of energy was deposited, leaving the system behind in a state similar to the high-temperature metallic phase.

References:

- [1] Perfetti et al., *New J. Phys.* **10**, 053019 (2008).
- [2] Dean et al., *Phys. Rev. Lett.* **106**, 016401 (2011).

Can charge-density waves and Mott cooperate ?

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We present a theoretical study of systems of correlated electrons coupled to lattice displacements, where the motivation comes from the electronic properties of the insulator 1T - TaS₂. It seems well established that 1T - TaS₂ at low temperatures changes from an incommensurate into commensurate charge density-wave (CDW) structure with odd number electrons in the low-T unit cell. The natural candidate for the insulating behaviour is then the opening of the Mott gap. We address the question which could be conditions that in the ground state CDW cooperates with the Mott mechanism of metal-insulator transition, and more specific which can be minimal models to observe such an effect. As the toy model we first study the one-dimensional Hubbard model coupled to classical lattice deformations. Taking the quarter filling as the example, the ground state changes from the Peierls-distorted lattice in the non-interacting case into the Mott-driven insulator at large Hubbard repulsion U . While the Hartree-Fock treatment show a transition between two regimens, the exact-diagonalization and the DMRG study of the model reveals the crossover from the $2k_F$ lattice and CDW deformation into the antiferromagnetic $4k_F$ deformation. The implications for higher dimensional systems, in particular for correlated models of layered systems, will be also discussed.

Exactly solvable cellular automaton model of steady state non-equilibrium transport

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We propose an interacting many-body space-time-discrete Markov chain model, which is composed of an integrable deterministic and reversible cellular automaton on a finite one-dimensional lattice, and local stochastic Markov chains at the two lattice boundaries which provide chemical baths for absorbing or emitting the solitons. Ergodicity of this many-body Markov chain is proven for generic values of bath parameters, implying existence of a unique non-equilibrium steady state. The latter is constructed exactly and explicitly in terms of a particularly simple form of matrix product ansatz, the so-called patch ansatz. This gives rise to an explicit computation of observables and k-point correlation functions in the steady state as well as the construction of a nontrivial set of local conservation laws. Feasibility of an exact solution for the full spectrum and eigenvectors (decay modes) of the Markov matrix is suggested as well. We conjecture that our ideas can pave the road towards a theory of integrability of boundary driven classical deterministic lattice systems.

Properties of the hidden quantum state in 1T-TaS₂

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Recently, stable switching to the hidden (H) quantum state was achieved by photoexcitation with ultrashort 35-fs laser pulse [1] as well as by 30-ps-long electrical pulse [2] in the charge-density-wave material 1T-TaS₂. Previously we reported [3,4] that at low temperature the lifetime of the state becomes unmeasurably long. Large resistive switching allows the material to be implemented in ultrafast non-volatile memory devices. Since the reported effect is the first observed example of switching to the hidden state which is essentially stable, it also attracts a lot of scientific interest and possibly guides to another photoinduced states with high stability in different systems.

Trying to find the crucial properties, which lead to the remarkable stability of the H state and to get additional information on its properties we performed scanning tunnelling microscopy (STM) in the switched state and in the ground state. It reveals the formation of domain walls in the H state and closure of the gap around Fermi level. Under continuous STM imaging the H state gradually relaxes, domain walls move towards the centre of the switched region and eventually disappear.

While the switching from the thermal commensurate to the H state can be performed rapidly on the picosecond timescale, the erasing procedure was shown to be relatively slow process as it involves heating of the device. We discuss possible alternative non-thermal ways of reverting the commensurate order in the material by pulsed laser or by electrical current.

References:

- [1] L. Stojchevska et al., *Science* 344, 177 (2014).
- [2] I. Vaskivskyi et al., *arXiv* (2014).
- [3] I. Vaskivskyi et al., *Science Advances* 1, 6 (2015).
- [4] I. Vaskivskyi et al., *Dynamics of Quantum Many-Body Systems far from Equilibrium*, Krvavec (2014).

Conserved quantities in integrable and perturbed integrable models

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Various studies have recently suggested that steady states of integrable systems are fully specified by local conserved quantities. This conjecture is known as the generalized Gibbs ensemble and has been well established in systems which can be mapped on noninteracting particles. Application of this concept or its possible extension to other integrable systems relies on completeness of the set of conserved quantities [1]. We outline a procedure for identifying a complete set of local and quasilocal conserved operators in integrable lattice models. As an example we study the anisotropic Heisenberg spin-1/2 chain and show that besides the known local operators there exist novel quasilocal conserved quantities in all symmetry sectors [2]. We discuss also an extended version of this approach, which allows for identifying approximately conserved quantities in models perturbed away from integrability [3]. In the long-time regime, these quantities fully determine correlation functions of all local observables. Applying the latter algorithm to the perturbed Heisenberg model we find that the main effect of perturbation consists in expanding the support of conserved quantities. This expansion follows quadratic dependence on the strength of perturbation.

References:

- [1] M. Mierzejewski, P. Prelovsek and T. Prosen, Phys. Rev. Lett. 113, 020602 (2014).
- [2] M. Mierzejewski, P. Prelovsek and T. Prosen, Phys. Rev. Lett. 114, 140601 (2015).
- [3] M. Mierzejewski, T. Prosen, and P. Prelovsek, arXiv:1508.06385

Towards an ab-initio simulation of nonequilibrium phenomena in correlated materials

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The combination of the GW ab-initio method and dynamical mean-field theory (DMFT) allows a fully self-consistent treatment of dynamical screening and correlation effects in solids [1]. I will report on recent progress in implementing fully self-consistent equilibrium GW+DMFT calculations for model systems [2] and realistic materials [3]. This formalism also holds great promise for nonequilibrium applications and may in the not too distant future enable material specific predictions of nonequilibrium phenomena. As a first step in this direction, I will present results from extended DMFT simulations of a Hubbard model with long-range interactions, and in particular discuss the changes in the screening environment, which occur after the injection of charge carriers into a Mott insulator by an electric field pulse [4].

References:

- [1] S. Biermann, F. Aryasetiawan, and A. Georges, *Phys. Rev. Lett.* 90, 086402 (2003).
- [2] L. Huang, T. Ayrál, S. Biermann, and P. Werner, *Phys. Rev. B* 90, 195114 (2014).
- [3] L. Boehnke, F. Nilsson, F. Aryasetiawan, and P. Werner, in preparation.
- [4] D. Golez, M. Eckstein, and P. Werner, *Phys. Rev. B* 92, 195123 (2015).

Sub-gap states in the Anderson impurity model at finite temperature and spectroscopy at finite bias voltage

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A magnetic impurity in a superconductor induces sub-gap bound states. They give rise to delta-peaks in the zero-temperature spectral function. The delta-peaks persist at finite temperatures, but for quantum (i.e., interacting) impurities there is also continuous sub-gap background due to inelastic scattering of thermally excited Bogoliubov quasiparticles. I will describe the first attempts at determining the temperature dependence of the spectral function for the single-impurity Anderson model with superconducting continuum, and its relevance in the interpretation of the tunnelling spectroscopy at finite bias. An unexpected result of these calculations is the observation of a further spectral resonance that appears at finite temperatures in the strong-hybridization (valence fluctuation) regime. A possible interpretation is that this is a “high-order” Shiba bound states due to exchange coupling of the thermally occupied “first-order” sub-gap excited doublet state.

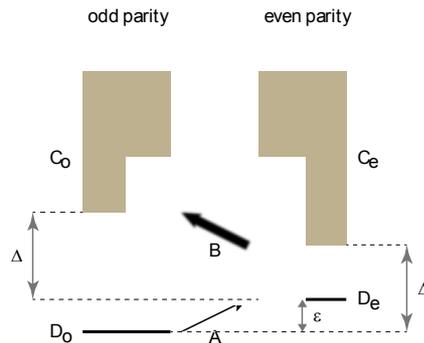


Figure 1: Transitions between the many-particle eigenstates contributing to the spectral function.

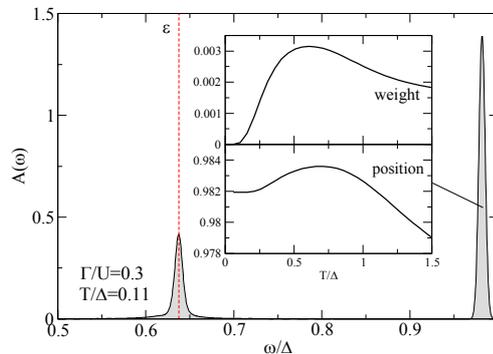


Figure 2: Thermally generated "high-order" Shiba resonance in the valence fluctuation regime.

Ultrafast modulation of magneto-optical Faraday effect

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In today's science and technology the Faraday rotation serves as powerful tool for probing magnetism as well as underlies the basic operational principles of magneto-optical modulators. Here we suggest a conceptually new approach for an ultrafast modulation of the Faraday rotation. Using paramagnetic terbium gallium garnet (TGG) we demonstrate the feasibility of such a magneto-optical modulation with a frequency up to 1.1~THz, continuously tunable with the help of an external magnetic field. Besides the novel concept for ultrafast magneto-optical polarization modulation, our findings clearly demonstrate the importance of accounting for light propagation effects in the interpretation of pump-probe magneto-optical experiments.

To demonstrate the effect of ultrafast modulation we employed two color time resolved pump probe technique in transmission and reflection geometries. To explain the effect of the modulation, we propose the model of a counter-propagating probe pulse with respect to a pump induced via the optical Kerr effect a dichroic region. In an external magnetic the linearly polarized pump and probe pulses experience the Faraday rotation. If the probe pulse is behind the pump, then the part of the pump reflected from the second face of the crystal can counter-propagate through the probe which via the optical Kerr effect will acquire polarization rotation (Fig.1(a,c)). If the probe pulse is ahead of the pump, then the polarization of the reflected probe is modulated by the pump due to the same Kerr effect, but the signal appears in the negative time delay (Fig.1(b,d,e)). The Kerr effect depends on the mutual orientation of the polarization of the two pulses at the moment of encounter defined by the time delay between them. The signal quenches as soon as the time delay between the two pulses becomes so long that the probe pulse cannot encounter with the counter propagating pump any longer (Fig.1(a,b)). Our theoretical calculations are in a full agreement with the experimental observations.

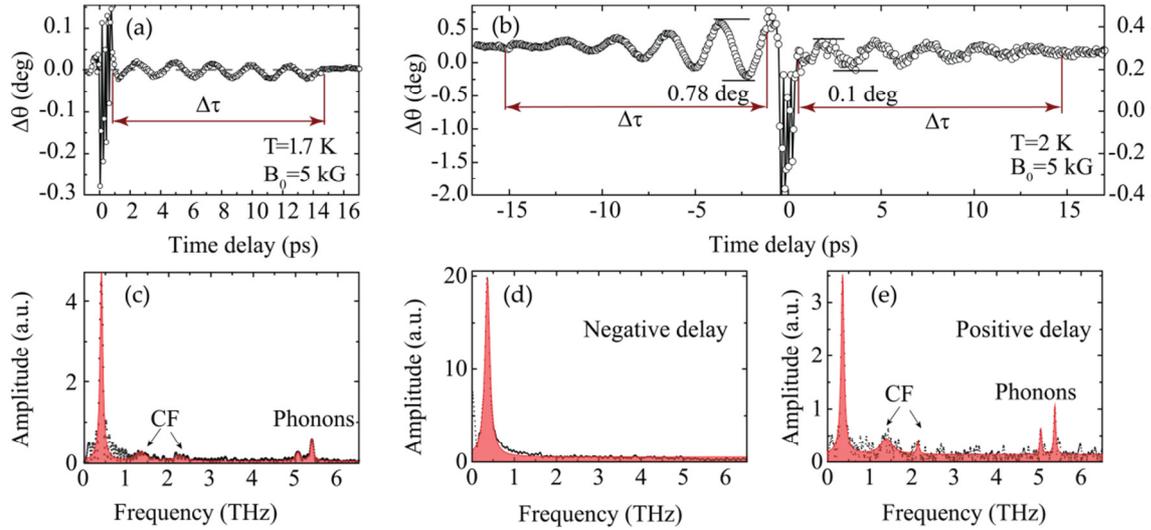


Figure 1. (a,b) Typical temporal response of the pump induced Faraday rotation of the transmitted and reflected probe, respectively at 5 kG and 1.7 K. Arrows show the limited time window of the observed oscillations. Vicinity of the 0 ps corresponds to the temporal overlap. (c) FFT spectra of the signal shown in panel (a) in the positive delay; (d,e) of signal in panel (b) for the negative and positive delay, respectively.

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Dynamics of resistive state in thin superconducting channels

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When a current in the thin superconducting channel exceeds its critical value, the current-voltage characteristic shows series of steps and demonstrates hysteresis. We theoretically study how the dynamics of the resistive state in narrow superconducting channels shunted by an external resistor depends on channel's length L , the applied current J , and parameter u characterizing the penetration depth of the electric field in the nonequilibrium superconductors [1,2]. We found out that the steps in the current-voltage characteristic can be associated with the bifurcations of either the steady state or oscillatory solution. We revealed typical bifurcations which induced the singularities in current-voltage characteristics. Our results in the range of higher currents show that these bifurcations can substantially complicate dynamics of the order parameter and eventually lead to the appearance of such phenomena as multistability and chaos. We also demonstrate that hysteresis loop between two different periodic solutions may be controlled by the external noise or by the current pulse [3].

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Optically assisted switching between phase slip configurations in superconducting nanowires

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Upon exceeding critical current the superconducting nanowire enters the dynamical resistive state characterised by periodically appearing normal regions in which phase of the order parameter slips by 2π - phase slip centers (PSCs). For a given current multiple dynamical configurations are possible, characterized by different spatial and temporal behavior of the order parameter. Experimentally they can be easily distinguished by the time-averaged voltage drop on the nanowire.

Switching between different PSCs can occur spontaneously giving rise to a “telegraph noise” behavior of resistance. This however occurs in a narrow region of currents and hard to investigate. Recently electrical noise assisted switching has been demonstrated allowing better understanding of the stability of phase slip centers. In this talk we present measurements of the PSCs in δ -MoN nanowires with $T_c=11$ K. We report switching between different PSCs after application of the single 50-fs laser pulse of variable wavelength, including switching into PSC configurations apparently unachievable in quasiequilibrium conditions

Time-resolved XUV photoemission: a new clue for understanding the ultrafast dynamics in copper oxides

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High temperature superconductivity in copper oxides is among the most intriguing phenomena concerning strongly-correlated materials. Cuprates are characterized by a complex Fermi Surface, where nodal and antinodal quasiparticles display markedly different properties and are thought to hide the key for understanding the unique properties of cuprate superconductors [1]. Here we combine the unique momentum resolution of ARPES with a non-equilibrium approach to study the dynamics of quasiparticles over the entire Brillouin Zone of the Y-Bi2212 compound, by using an ultrafast HHG XUV photon source [2]. For the first time, we map both the nodal and antinodal excitations, revealing a peculiar transient surplus of positive charge at the antinodes. Moreover, we study the dynamics of the Mott-like excitations involving O 2p states lying 1.5 eV below the Fermi level. In cuprates, these high-energy excitations are intertwined with the electronic properties at the Fermi level [3], and a challenge is to understand how the high-energy physics associated to Mott-like excitations is involved in the condensate formation. We reveal a long-lasting dynamics of the O 2p states, that is interpreted within the three-band Hubbard model where holes interact with the antiferromagnetic background [4]. Finally, we discuss a novel approach for studying via TR-ARPES with high energy and momentum resolution and limited space charge the quasiparticle dynamics over the entire Brillouin Zone of copper-oxides, and discuss the most recent developments in the field.

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How rapidly do ordered states form in cuprates?

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Separating the different relaxation and collective recovery processes using 3-pulse techniques gives us some interesting new insights into the nature of the ordering of collective states in cuprates. Of particular interest is the distinct difference in the single-particle relaxation and pseudogap recovery rates, which occur on ~ 250 fs and ~ 600 fs timescales respectively at all temperatures above the superconducting T_c .¹ In contrast, the superconducting quasiparticle relaxation time and superconducting recovery time are indistinguishable near T_c and are in the range $3 \sim 5$ ps, depending on the system². Elucidating these observations, a systematic temperature and doping dependence study of the pseudogap photo-destruction and recovery in coherent quench experiments reveals a marked absence of critical behaviour of the elementary excitations, which implies symmetry breaking in the absence of collective electronic ordering beyond a few coherence lengths on short timescales^{1,3}. The fact that the single-particle excitations in the PG relax faster than the PG recovers, indicates that the PG is a correlated state, and not a simple doped semiconductor. The data imply ultrafast carrier localization into a textured polaronic state. These observations also set a limit on how fast superconductivity can form within a non-equilibrium situation, which is of significance in the search for photoinduced superconductivity.

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How fast does the quasiparticle band emerge in a strongly correlated metal?

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When a Mott transition is approached from the metallic side, a narrow quasi-particle band emerges at the Fermi energy. Using nonequilibrium dynamical mean-field theory (DMFT) and a slave-rotor impurity solver, we simulate a setup in which the quasiparticle band is destroyed by a strong excitation (which leads to hot electrons), and reforms as the excitation energy is passed from the electrons to the lattice. Within DMFT, the quasiparticle peak corresponds to the Kondo resonance in an effective Anderson impurity model. However, while the timescale for the formation of the Kondo resonance is uncertainty-limited, i.e., it is given by the inverse width of the peak itself, the behaviour is entirely different for the formation of the quasiparticle band. The timescale for the restructuring of the density of states is determined by an electronic bottleneck timescale which is not reflected in single-particle properties such as quasiparticle decoherence time or quasiparticle lifetime. The finding implies a slowdown in the relaxation at the paramagnetic Mott transition, which could be seen in the optical conductivity, as the system remains in a bad metal state until quasiparticles are being formed.

Evidence for Pre-Formed Cooper Pairs in the Pseudogap Phase of Slightly Underdoped $\text{NdBa}_2\text{Cu}_3\text{O}_{6+x}$

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In the last years ultrafast experiments have contributed to shed new light on high-temperature superconductivity. In particular, tailored excitation in the mid-infrared spectral range was demonstrated to suppress competing structural and electronic orders and to promote a highly coherent state in several underdoped cuprates [1 - 4]. In $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ this transient state was found to persist up to room temperature, evidenced by the enhancement of the superfluid strength in the THz response. The question whether the high coherence is the signature of a perfect conducting or of an exotic superconducting state at nonequilibrium still remains open. Here, we address this problem from a spectroscopic point of view, by investigating a slightly underdoped sample of $\text{NdBa}_2\text{Cu}_3\text{O}_{6+x}$ through ultrafast spectroscopy in the optical regime. The use of a broadband detection scheme enables us to reveal evidence for quasiparticle (QP) excitation up to a temperature T_{ONS} , which is higher than the superconducting critical temperature T_{C} but lower than the pseudogap temperature T^* . The existence of a QP spectral signature in the pseudogap phase, together with its peculiar temporal evolution and temperature dependence, can be directly related to the presence of a pairing gap for QP excitation. In the same experiments, we also track the temperature evolution of the coherent Ba mode, which represents a sensitive probe of pairing correlations, and we observe an anomaly of its intensity also at T_{ONS} . The pump-probe experiments are complemented by equilibrium spectroscopic ellipsometry measurements, covering a wide spectral range from the far-infrared to optical frequencies, which confirm the existence of such temperature scale T_{ONS} between T_{C} and T^* . The observation of preformed pairs under nonequilibrium conditions not only provides important spectroscopic information on the dynamics of the local pairing correlations above T_{C} , but also opens new exciting perspectives towards the ultrafast control of these incoherent pairs.

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Exact non-adiabatic qubit manipulation on Rashba rings

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First we will present exact solutions for an electron in a quantum wire with time dependent spin-orbit interaction and driven by external time-dependent potential [1,2]. By the virtue of the exact solution one can construct analytically the corresponding geometric Anandan phase or in the adiabatic limit the Wilczek-Zee phase, which enables holonomic qubit transformations. By breaking the time reversal symmetry the results lead to the Aharonov-Anandan phase and in the adiabatic limit reproduce the usual Berry phase.

Next the result will be generalized and an exact solution will be presented for the time-dependent wavefunction of a Kramers doublet which propagates around a quantum ring with tuneable Rashba spin-orbit interaction [3], Figure 1(a). By propagating in segments it will be shown that Kramers-doublet qubits may be defined for which transformations on the Bloch sphere may be performed for an integral number of revolutions around the ring. The conditions for full coverage of the Bloch sphere will be determined and explained in terms of sequential qubit rotations due to electron motion along the segments, with change of rotation axes between segments due to adiabatic changes in the Rashba spin-orbit interaction, Figure 1(b). Prospects and challenges for possible realizations will be discussed for which rings based on InAs quantum wires are promising candidates [4].

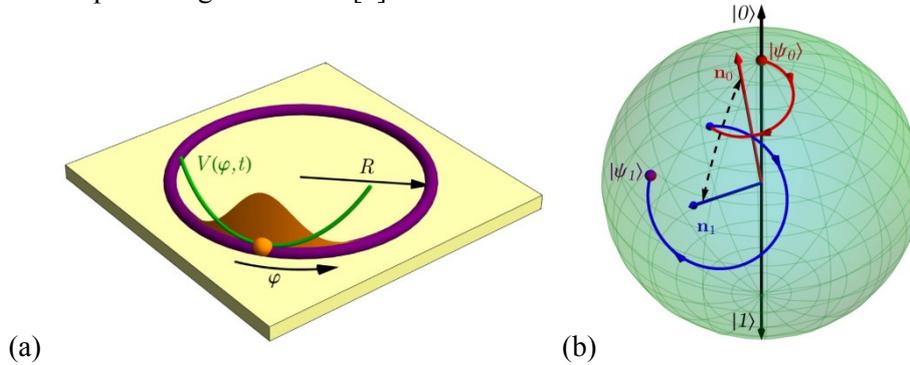


Figure 1: (a) Ring system with time dependent driving potential $V(\varphi, t)$. (b) Bloch sphere: example of a two-step qubit transformation.

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Superfluorescence of CuCl Quantum Dots Assembly

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Superfluorescence is a cooperative spontaneous emission from an assembly of excited two-level systems. When the distances between the excited two-levels are sufficiently short compared to wavelength of the radiation field, it is possible that the transition dipole moments are coherently coupled spontaneously, which is triggered by fluorescence, then the assembly radiates photons as a pulsed emission, that is, superfluorescence. The change in peak intensity and pulse width is proportional to N^2 and $1/N$, respectively, where N is the number of the two-levels. In addition, the delay time to the peak is shortened as the value of N increases. The superfluorescence has been mainly researched for atoms and molecules. In addition, the semiconductor quantum dots (QDs) assembly is also a plausible system to generate superfluorescence because a QD can be recognized as an isolated quantum system. The short radiative time of an exciton (an electron-hole pair) in a semiconductor is expected to give rise to fast establishment of coherent coupling among the excited QDs, and hence, it is possible to generate ultrashort pulsed emission of the superfluorescence. However, an inhomogeneous spectral width induced by dot-size distribution and the dephasing rate of the dipole moments result in degradation of coherent coupling. A competition between the radiative rate and dephasing rate is an important for the generation of the superfluorescence.

The generation of the superfluorescence using CuCl QDs assembly embedded in NaCl single crystals, which is illustrated in Figure 1(a), is performed. CuCl is an appropriate material for the study of the exciton and biexciton (bound two exciton pair) because of their large binding energies. Resonant two-photon excitation of the biexcitons is useful to generate a complete population inversion between the biexciton and exciton levels, as shown in Figure 1(b). Figure 1(c) shows the excitation density dependence of the photoluminescence time profiles of the biexcitons. At a low excitation density, the time profile indicates the amplified spontaneous emission. The time profile changed to a pulsed shape having a large width as the excitation density increases up to 2.4 mJ/cm^2 , which indicates a transition from the amplified spontaneous emission to the superfluorescence. By further increasing the excitation density, the delay time to the peak decreased and the time width became narrower. These are typical behaviors of the superfluorescence. In addition, the temperature dependence of the PL time profiles and effect of the size distribution to the generation of the superfluorescence will be reported.

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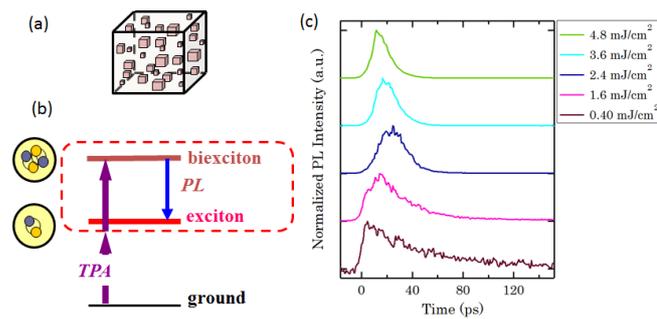


Figure 1: (a) Illustration of CuCl quantum dots embedded in a NaCl matrix. (b) Energy scheme of an exciton and a biexciton state. The biexciton was excited through the resonant two-photon absorption process. (c) Excitation density dependence of the photoluminescence time profiles of the biexcitons.

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Charge photogeneration in few-layer MoS₂

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Bulk MoS₂ is a layered transition metal dichalcogenide indirect bandgap semiconductor with the bandgap about 1.2 eV. Due to a strong light-matter interaction optical spectra of MoS₂ show strongly bound Wannier-Mott excitons (binding energy is about 0.5 eV). On the other hand, the demonstration of a photodetector based on monolayer of MoS₂ with reasonable good characteristics suggests that photoexcitation creates also weakly bound carriers in MoS₂. I present results of pump-probe spectroscopy on few-layer MoS₂. I discuss exciton dissociation to charge carriers on the time scale of 700 fs and also the efficiency of this mechanism depending on the pump energy and different fluences.

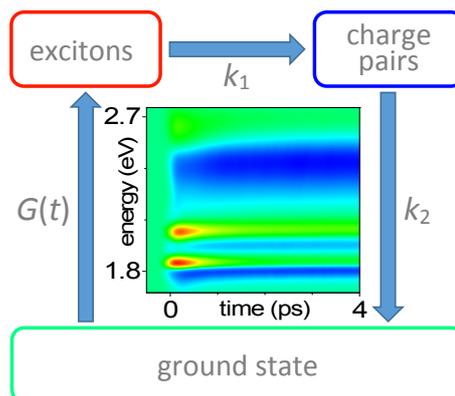


Figure : Scheme of the photoexcitation dynamics of excitons and charges. Contour plot of the measured $\Delta T/T$ (in %)

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Exciton and charge carrier dynamics in few-layer WS₂ and dynamics thickness dependence in MoS₂ few-layer selection.

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Semiconducting transition metal dichalcogenides (STMDs) have been applied as the active layer in photodetectors¹ and solar cells², displaying substantial charge photogeneration yields. However, the large exciton binding energy, which increases with decreasing thickness (number of layers), as well as the strong resonance peaks in the absorption spectra suggest that excitons be the primary photoexcited states. Detailed time-domain studies of the photoexcitation dynamics in STMDs exist mostly for MoS₂³ but without paying attention to the influence of the thickness in lifetimes. Here, we use femtosecond optical spectroscopy to study the exciton and charge dynamics following impulsive photoexcitation in few-layer WS₂ and size selected MoS₂. In the case of WS₂ excitons as the primary photoexcited state is confirmed and find that they dissociate into charge pairs with a time constant of about 1.3 ps. Subsequently, these charges diffuse through the samples and get trapped at defects, such as flake edges or grain boundaries, causing an appreciable change of their transient absorption spectra. This finding opens the way to further studies of traps in STMD samples with different defect content. In the case of MoS₂ quantum confinement and its influence on the exciton dissociation dynamics is observed for different flakes thickness.

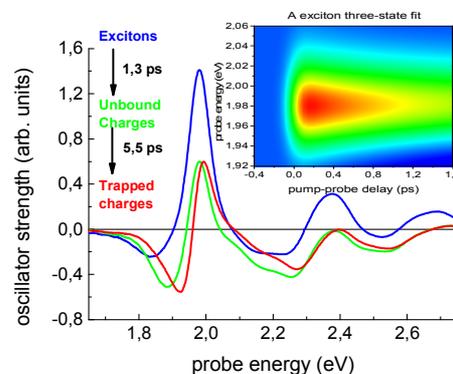


Figure 1: WS₂ absorption cross section spectra for the different photoexcited states and fitting of the A exciton dynamics with our model (inset).

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Photoinduced Charge Transfer between MoS₂ and organic semiconductors

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Photoinduced charge separation is the central step in many photochemical reactions as well as for the operation of photodetectors and solar cells. In materials with large exciton binding energies, such as conjugated polymers, carbon nanotubes, or two-dimensional inorganic semiconductors such as MoS₂, efficient charge separation occurs only at interfaces where it is energetically favourable and one material acts as electron donor and the other as acceptor. Efficient donor-acceptor combinations are often hard to predict since the exact energies of the valence and conduction bands or highest occupied and lowest unoccupied molecular orbitals depend strongly on the environment. Here we use femtosecond optical spectroscopy to directly monitor the photoinduced charge dynamics in different combinations of MoS₂ flakes obtained from liquid exfoliation and organic semiconductors. We find both an unexpectedly inefficient combination as well as a highly promising combination where an efficient charge transfer occurs in the first few picoseconds after photoexcitation. This suggests a novel material combination for photodetectors and bulk heterojunction solar cells, which pools the advantages of organic solar cells – light weight and mechanical flexibility – with the superior charge mobility and the extraordinarily strong light-matter interaction of MoS₂.

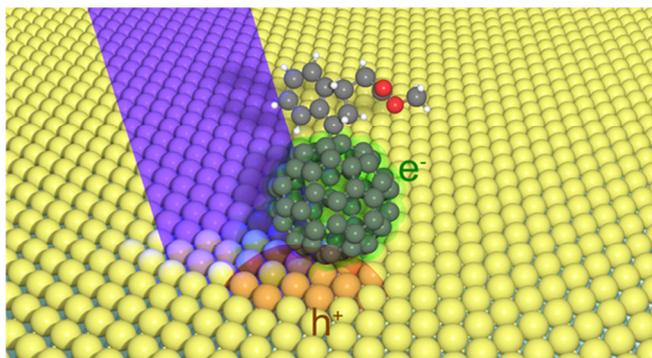


Figure 1: Artist's representation of photoinduced charge transfer. Image courtesy of J. Strle.

Emergence of soliton phase in Q1D organic conductors as evidenced by nonlinear transport

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It is now well established [1-4] that in Bechgaard salts, $(\text{TMTSF})_2\text{X}$ ($\text{X}=\text{PF}_6, \text{ClO}_4$) spin-density wave (SDW), near its critical point, coexists with small metallic/superconducting (SC) domains elongated, counterintuitively, in the direction of the weakest conductivity. The mechanism behind the formation of such an unusual spatial texture is still being debated [1,3,4], with the two approaches, soliton phase theory [5] and macroscopic segregation [4], being most promising. However, neither of them consistently accounts for all the observed effects in the coexistence region [3].

Previous experiments [1-4] were using linear transport measurements to study the phase coexistence and were unable to observe directly the soliton phase in SDW, were it the mechanism responsible. Here we analyse the nonlinear transport behaviour with the external excitation large enough to induce collective SDW response and hence probe the soliton phase directly. In the macroscopic segregation scenario such a probe will give only the homogeneous SDW response, thus allowing us to distinguish between the two options.

We find that highly conducting state in the coexistence region in $(\text{TMTSF})_2\text{ClO}_4$ is destroyed above certain threshold current – the behaviour exactly opposite to that of the homogeneous SDW and hence to that expected in the macroscopic segregation scenario. Such behaviour is limited to the coexistence region, being the most prominent close to the homogeneous SDW boundary and vanishing towards SDW endpoint. We characterize the nonlinearity properties at different temperatures and magnetic fields and discuss links to existing soliton or bi-soliton phases in Q1D systems.

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Field Induced dissociation of Excitons in MoS₂ monolayer

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Two-dimensional Transition Metal dichalcogenides (TMDs) are an emerging material family with a wide range of potential application in electronics, optoelectronics and energy harvesting. Previous studies have proved that, despite the increase of the exciton binding energy (from 45 and 130 meV for bulk MoS₂ to 0.4-0.9 eV for monolayer), monolayer MoS₂ shows a photovoltaic effect¹ and potential as a photodetector.² A first possible scenario of the photoexcitation dynamics has been proposed following the observation of the excitons that dissociate into charges with a characteristic time constant of 700fs in few-layer MoS₂.³ We exploit field assisted ultrafast spectroscopy to probe exciton dynamics and charge generation when an in-plane field is applied and charge injection is prevented by the appropriate gate voltage. When no field is applied, we observed a behaviour of the starting photoexcited population dominated by hot excitons that relax with a characteristic time of 800 fs, branching into mainly relaxed excitons and a smaller population of dissociated electron-hole pairs. For an electric field intensity around 8000V/cm, applied between drain and source, we observed an increased charge formation, detected as an enhancement of their characteristic photo-induced absorption features.³ The characteristic time of the exciton dissociation is 600 fs, slightly less than the exciton relaxation time without electric field. Hence the field-induced enhancement of the exciton dissociation is present during most of the relaxation.

Our results show that the limited yield of photoinduced free charges in MoS₂ can be significantly increased by applying a moderate in-plane electric field. From this we can deduce that photovoltaic cells can be made more efficient by engineering a built-in electric field, e.g. by using different metals for source and drain.

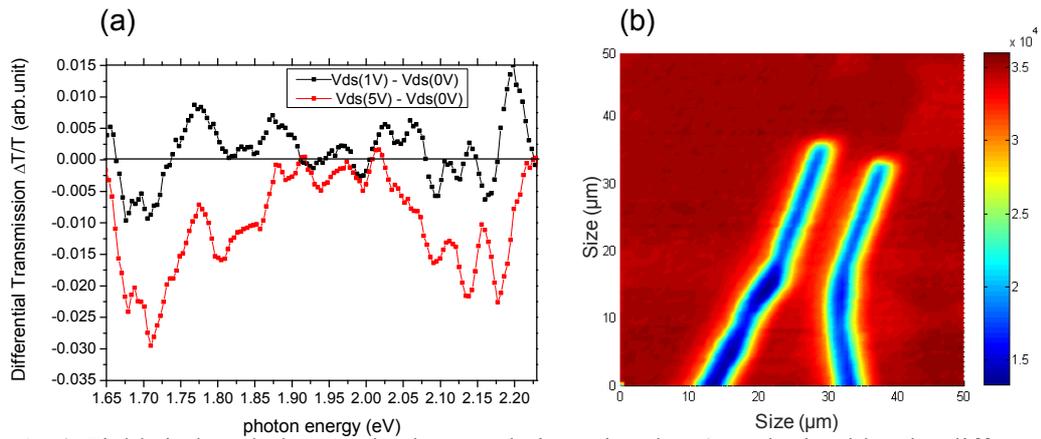


Figure 1: a) Field- induced changes in the population: signal at 2ps obtained by the difference between $(\Delta T/T)^{\text{field}} - (\Delta T/T)^{\text{no-field}}$. b) Optical map at 500nm of the MoS₂ transistor.

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Light-induced transition from hard to soft gap in CDW conductor NbS₃ (phase II) at 77 K

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Phase II of chain-like quasi-one-dimensional conductor NbS₃ exhibits up to three Peierls transitions, depending on growth conditions¹. Upper transitions occur above room temperature at $T_{P1} = 360$ K, $T_{P0} = 620$ K² whereas the lower one occurs at $T_{P2} = 150$ K. The superstructure observed in TEM and X-ray measurements proves two distinct charge density waves (CDW's) coexistence at room temperature³. While CDW₀ corresponding to T_{P0} is generally strongly pinned, the Shapiro steps experiments demonstrate emergence of coherent long-range ordered state below each of T_{P1} and T_{P2} , with high coherence of sliding CDW₁ and ultimately high velocities of coherent CDW₁ motion at room temperature. Such a velocity is obtained from the frequency of CDW₁ synchronization to external radiation, f_0 , where $f_0 = I_{CDW}/MeN$ and I_{CDW} is the CDW current, e - the elementary charge, $M \approx 2$ - the number of electrons per CDW wavelength per chain, N - the total number of conducting chains. Room temperature frequencies for NbS₃ (phase II) reach the highest known value of 20 GHz and may be enhanced⁴. Only one chain of eight per unit cell contributes to CDW₁ conductivity.

However the nature of the ordered state below $T_{P2} = 150$ K, which is observed only in crystals grown under certain conditions, is poorly understood. The I_{CDW}/f_0 value for this T_{P2} state is found to vary with samples and tends to reach very low values, which for the classical CDW compounds⁵ would correspond to 0.01 conducting chain per unit cell. Such observation raises concerns on eligibility of classical CDW framework in this case. The ongoing microscopic and spectroscopic studies highlight the role of the sulphur vacancies in the emergence of T_{P2} state².

In the present work photoconduction spectra of NbS₃(II) crystals are studied, in a temperature range 77–155 K. The optical gap $2\Delta = 0.43$ eV is found at 77 K. Close to the gap edge the photoconductivity σ_{ph} , normalised by photon quantity, is proportional to $(\omega - 2\Delta)^\gamma$ where $\hbar\omega$ is photon energy and $\gamma \approx 1$ at 77 K and increases with increasing temperature up to $\gamma \approx 4$. At the temperatures from 130 K to 155 K $\sigma_{ph} \approx \omega^4$ fits experimental data in the whole measured range of photon energy from 0.1 to 1.3 eV. The same change in $\sigma_{ph}(\omega)$ dependence from “hard” gap to “soft” gap can be induced at 77 K by applying constant additional illumination by light emitting diode ($\hbar\omega = 1.3$ eV) while the heating effect of illumination is eliminated by firm thermal contact and the atmosphere of exchange gas. The possibility of screening-induced transition into excitonic insulator phase is discussed.

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Femtosecond relaxation dynamics in CDW molybdenum oxides η -Mo₄O₁₁ and Mo₈O₂₃

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Molybdenum oxides exist in many stoichiometries like MoO₂, MoO₃, Mo₄O₁₁, Mo₅O₁₄, Mo₈O₂₃, Mo₉O₂₆ where properties strongly depend on the structure [1] varying from metallic in the case of MoO₂ to insulating for MoO₃. Molybdenum oxide Mo₈O₂₃ is one of the so called molybdenum suboxides Magneli phases. The crystal structure is monoclinic with space group P2/c. The material has two known temperature transitions, the first at 350 K where it forms a modulated phase with an incommensurate wave-vector and the second one at 285 K where a commensurate CDW is formed by a lock-in transition [2]. Molybdenum oxide Mo₄O₁₁ is another type of the molybdenum suboxides Magneli phases. It is a quasi 2D system with metallic behavior. The monoclinic structure of Mo₄O₁₁ also known as η -Mo₄O₁₁ has two Peierls transitions at 105 and 35 K [3,4] where two incommensurate charge density wave (CDW) states are formed.

We present the first systematic study of the transient reflectivity $\Delta R/R$ in single crystals of Mo₈O₂₃ and Mo₄O₁₁ by means of the femtosecond optical time resolved spectroscopy. Temperature, polarization and fluence dependence of dynamics was investigated with two different pump-photon energies (3.1 eV and 1.55 eV) at temperatures below the CDW transition temperatures T_{CDW} . In the CDW state of Mo₈O₂₃ a complex coherent phonon response appears in the transient reflectivity showing a narrow antiresonance. In the case of Mo₄O₁₁ we observed a critical slowing down of the relaxation dynamics at the first CDW transition. In the CDW state 6 strong coherent phonons appears with no clear softening suggesting weak coupling to the collective electronic order parameter.

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Relaxation dynamics of the excitonic insulator

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In the 1960's, a new insulating phase was predicted in a semimetallic or semiconducting systems, which exhibit gap due to bound states between holes and electrons, called exciton¹. We represent the nonequilibrium study of the one dimensional two band problem with long range interaction within the time-dependent random phase approximation (tRPA). In the equilibrium system exhibits excitonic insulator behaviour with opening of the gap. By exciting the system we can induce the dynamical phase transition to the unordered phase and critical slowing down of the relaxation is observed. We will show that destroying the excitonic correlations has strong effects on the dynamics of screening.

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Exact solutions for finite time quench protocols in Tomonaga-Luttinger liquids: from sudden quench to pumping.

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In our work we consider time-dependent parameter changes in the interacting Tomonaga-Luttinger liquid (TLL). Our focus is on those time-dependent protocols which allow for an exact analytical solution. Several such protocols can be identified. The solutions enables us to explore strong quench amplitudes, thus going beyond perturbative methods previously applied to this problem. I will present the results for the Green functions and density-density correlations during as well as after the quench. The light-cone picture remains applicable, however, the propagating front is delayed as compared to the sudden quench. This finding confirms previous numerical observations and can be attributed to the momentum dependence of the interaction vertex. I will discuss the spatial dependence of correlations for short and long times after quenching, also (for linear ramp protocol) for the non-perturbative regime of intermediate distances, and explain the occurrence of oscillations appearing behind the front. Finally, for periodic pumping protocol, I identify regime when the induced oscillations manifestly propagate throughout the system.

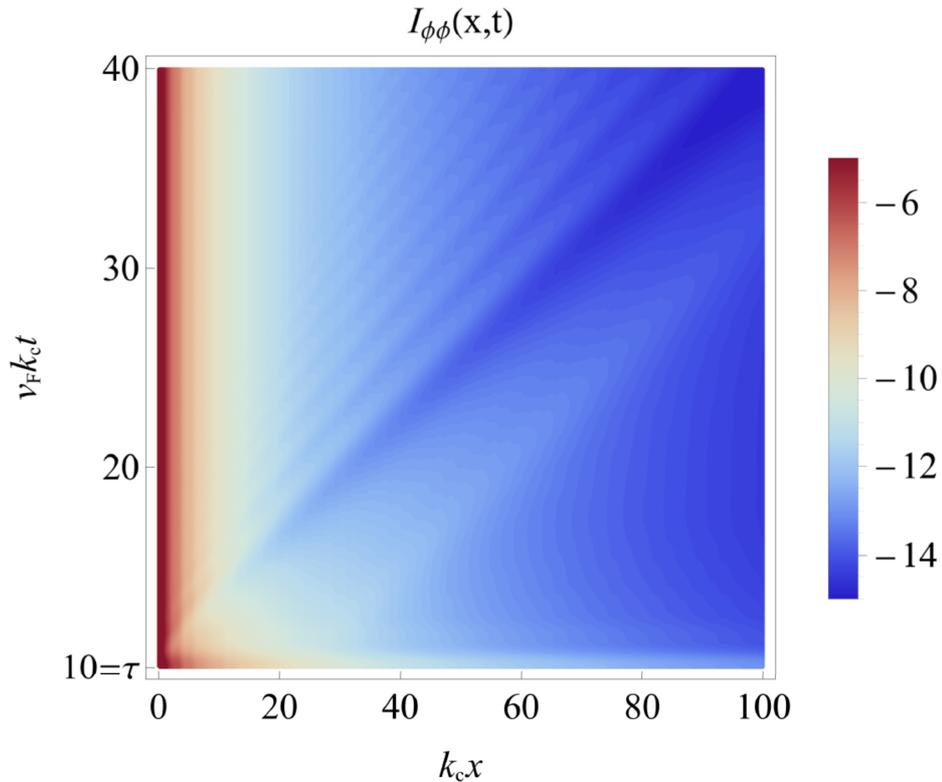


Figure x: Time dependent density-density correlation function after the linear ramp quenching of TLL.

Quasilocal conserved quantities in isotropic Heisenberg spin chain

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One of the main goals of statistical physics is to find an ensemble for the correct description of expectation values of local observables. Conserved quantities play the central role in this description [1] as well as in linear response theory [2]. Due to the integrability, quantum Heisenberg spin chain possesses an infinite set of local conserved operators in the thermodynamic limit. If we consider only the local conserved quantities, the statistical description is inaccurate [3,4]. To provide the correct description one needs to take into account the full set of quasilocal conserved quantities [5]. I will present, on an example of the Heisenberg spin chain, a general construction of the quasilocal conserved quantities, which are linearly independent from the local integrals of motion [6].

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