Nonequilibrium Dynamics in Correlated Systems and Quantum Materials

BOOK OF ABSTRACTS

December 15 – 18, 2019, Ambrož, Krvavec, Slovenia

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A new route to coherent Teraherz spin dynamics in solids

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The concept of coherence has been intensively pursued in the attempts to optically manipulate the macroscopic properties of solids on extreme timescales, since it allows to store information by imprinting a well-defined phase to the dynamics of a vibrational, electronic or spin ensemble. In the specific case of magnetic materials, coherent spin dynamics is induced by generating fundamental magnetic excitations, named spin waves or magnons, with wave vector either at the centre or at the edges of the Brillouin zone. In this talk I will present a novel route to the optical generation of collective coherent THz spin dynamics, which doesnot rely on the generation of the aforementioned magnon modes. In the magnetic semiconductor MnTe the electronic and spin degrees of freedom are intrinsically coupled, as expressed by a magnetic contribution to the band-gap energy. We exploit this coupling on the femtosecond timescale, by triggering coherent oscillations of the band-gap energy at the frequency of 5 THz, via the optical activation of a lattice mode. The spin system reacts as a driven oscillator displaying coherent harmonic dynamics with a 5 THz frequency, which does not match any frequency of optically accessable magnons in MnTe. We foresee that also the inverse effect is realisable, i.e. converting coherent magnons into charge dynamics on the (sub)-picosecond timescale: this phenomenon is potentially a milestone in the long-pursued and highly-investigated goal of an ever faster and more efficient spin-to-charge conversion.

Single-pulse magnetization reversal in ferromagnetic CoPt alloys

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Magnetic memory is the most widely used type of storage media for almost a century now. After decades of continuous and rapid improvements, current technology has already reached its fundamental limit in terms of the recording speed and storage density. New principles and new materials have to be investigated to keep up with the growing demand. Composite ferromagnets with large perpendicular magnetic anisotropy are proving their potential and are already being implemented in modern devices. Among them are Fe/Pt and Co/Pt compounds, which are probably the most studied, but their microscopic properties still can be hardly explained. All-optical magnetization reversal, recently observed in these systems [1,2], is believed to be a stochastic process, which relies on dichroic properties of the material and thus requires multiple switching pulses. This drastically limits their practical application.

Our recent time-resolved magneto-optical experiments suggest that another path for the magnetization switching exists, which might provide the key for single-pulse operation. We observe a transient reversal of the magnetization direction after a single laser pulse in partially disordered CoPt alloys by means of resonant Kerr spectroscopy. After complete demagnetization on the time-scale of ~150 fs, the magneto-optical signal changes its sign. We argue that this behaviour cannot be explained via the recently proposed OISTR (optically induced spin and orbital momentum transfer) effect [3, 4], which is thought to directly drive the magnetization dynamics by an electric field of the laser pulse and thus must happen on the time-scale of the laser pulse itself. Contrary, in the present experiments, we observe significantly slower dynamics, which calls for an alternative explanation.

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Emission of correlated jets from a driven matter-wave soliton

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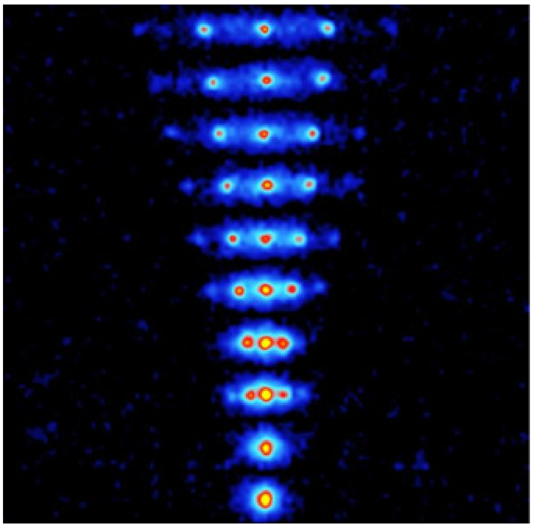
Modulating the interaction between the atoms in a Bose-Einstein condensate (BEC) can give raise to diverse phenomena depending on the frequency and amplitude of shaking [1]. When the frequency of modulation is tuned close to collective mode resonance, Faraday waves appear [2]. At low frequencies granulation of BEC is observed [1], whereas at high frequencies matter-wave jets are emitted [3-5]. We demonstrate the emission of correlated atom jets from a matter-wave soliton in a quasi-one-dimensional optical trap [6]. All stages of the jet emission are captured in a simple model based on the 1D Gross-Pitaevskii equation (GPE). Beyond the scope of the mean-field GPE simulation, the jet number correlations are investigated. We show sub-Poissonian statistics of the number difference between the left and right first-order jets in a regime of suppressed second-order jets [7].



Time evolution of first-order and second-order jets from a cesium matter-wave soliton in a quasi-one-dimensional geometry [7].

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[4] H. Fu, L. Feng, B. M. Anderson, L. W. Clark, J. Hu, J. W. Andrade, C. Chin, and K. Levin, Phys. Rev. Lett. **121**, 243001 (2018)
[5] L. Feng, J. Hu, L. W. Clark, and C. Chin, Science **363**, 521 (2019)
[6] T. Mežnaršič, T. Arh, J. Brence, J. Pišljar, K. Gosar, Ž. Gosar, R. Žitko, E. Zupanič, and P. Jeglič, Phys.Rev. A **99**, 033625 (2019)
[7] T. Mežnaršič, R. Žitko, T. Arh, K. Gosar, E. Zupanič, and P. Jeglič, arXiv:1905.10286

A time-resolved phase diagram of metastable states in 1*T*-TaS_2

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It was recently shown that a topological transition in 1*T*-TaS_2 leads to metastable chiral structures [1], while a jamming transition leads to metastable amorphous, hyperuniform electronic order [2]. Here we investigate the excitation conditions at which the various metastable states form and map out their time evolution after the photoexcitation. We use probes on different timescales to obtain 'snapshots' of the temporally evolving phase diagram in 1*T*-TaS_2. Optical three pulse Write-Pump-Probe (W-P-Pr) experiments probe repetitive switching on timescales below 10^{-12} s and around 10^{-3} s in different modes, depending on whether the W pulse comes before or after the P pulse respectively. The optical experiments rely on the measurement of collective mode excitation spectra and the different phases are identified based on their previously reported fingerprint signatures in transient reflectivity measurements. On the other hand, the STM directly probes the surface electronic order on a timescale of 10^2~10^4 s, and the states are distinguished by their charge ordering. We use photon density and temperature as control parameters to map out the phase diagram. The introduction of a time-domain axis enables systematic categorization of metastable emergent states on different timescales that are created through different phase transition mechanisms. The understanding of the time-evolution revealed by temporal phase diagrams opens the way to the development of new functionalities in metastable quantum materials based on configurational electron ordering.

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[2] Y. A. Gerasimenko *et al.*, Nat. Mat. **18**, 1078 (2019)

Time resolved momentum microscopy on FeRh thin films, revealing ultrafast time scales for AFM- to FM phase transition

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The development of a momentum microscope[1] for parallel electron detection, coupled to ultrafast extreme ultraviolet sources allows simultaneous observation of time-, momentum-, spin- and energy-resolved photo-electrons excited by femtosecond laser pulses[2]. In such experiments performed at the Free Electron Laser FLASH (DESY, Hamburg) we studied the dynamics of the electronic band structure upon laser induced phase transition between anti-ferromagnetic (AFM) and ferromagnetic (FM) phases of FeRh at the femtosecond time scale[3].

The photoinduced structural changes associated with the phase transition (the phase transition is accompanied by a structural expansion), have been shown to proceed on a timescale of a few tens of ps[4]. The appearance of the long-range ferromagnetic order, probed by time resolved MOKE[5], was shown to take place on the 100 ps timescale. Here, we track the changes in the electronic density of states (eDOS), making use of the fact that the phase transition results in vehement changes in the eDOS. By means of time resolved momentum microscopy, we show the formation of the eDOS, characteristic of the high temperature FM phase, on the timescale of 400 fs. The resulting changes are observed over large range of energies, from the Fermi level to a pronounced renormalization of electronic bands far below the Fermi level, and are well supported by ab-initio calculations. We thus reveal a new characteristic time of this process, and indicate an electronic origin to the AFM to FM photoinduced phase transition in FeRh. Note that the findings are not at odds with previous results of the slow lattice response and even slower buildup of the long range magnetic order.

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Research of ultrafast phase switching in 1*T*-TaS_2 by a picosecond electrical pulse

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One of the limitations for high performance computing is in slow and energy inefficient exchange of data between processor and memory [1]. Recent discovery of electronic switching between high and low resistance states of the 1T-TaS2 shows promising features for development of a high-speed and non-volatile memory device [2]. Electric pulses at picosecond time scales need to be used to probe intrinsic switching time of such a device, which is challenging due to limitations of signal generators and transmission line dispersion. We will present electronic circuit with a photoconductive switch on a semiconducting substrate CdMnTe that is designed for excitation and detection of picosecond electrical pulses generated by an ultrafast laser pulse [3, 4]. Picosecond pulse is generated by a frequency doubled laser pulse which transiently excites carriers to conducting band in a photoconductive switch. Another laser beam is focused between electrodes of transmission lines for measurement of a pulse electric field via Pockels effect. Transmission line architecture allows for efficient propagation of picosecond electric pulse towards the 1T-TaS2 crystal and measurement of the crystal resistance state.

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Quantum jamming and its topological implications

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Amongst the metastable states that have been recently discovered in transition metal dichalcogenides, the amorphous state created through a fast quench is perhaps the most unusual. In this talk I will discuss the mechanism for its formation, focusing on its topological properties in relation to metastability. I will also address a common puzzle that appears in complex quantum materials such as layered dichalcogenides and high-temperature superconductors which is highlighted by the jammed state, namely the co-existence of localized and delocalized states. The implication for superconductivity will be briefly discussed.

Free electrons as a probe of quantum excitations

I. Madan

Free-electrons are a well known tool for study of crystal structure, magnetic order, high-resolution imaging and elemental analysis in material science and condensed matter physics. Past decade has also proven that free-electrons can be used to study electromagnetic excitations, like surface plasmon polaritons with extremely high temporal and spatial resolution. An unexpected consequence of this research is an-indepth understanding of electron-light interaction, and in-particular a realisation that light can be used to engineer and control electron's wave-function [1–4].

To better control this interaction, systems with stronger electron-light interaction have been hypothesized. It is immideatly became clear that the strong-coupling regime should be practically achievable with a range of peculiar properties. A number of theoretical proposal has been published this year, proposing novel physical phenomena and apllications in such regime. [5–7]

In this talk I will present recent developements in control of electron wave-fucntion, will revise recent theoretical proposals on enhanced electron-light interaction and will put down experimental proposal on utilisations of these phenomena to access statistics of quantum excitations in condensed matter systems, their spatial and temporal extent.

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Eigenstate thermalization hypothesis and integrals of motion

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Even though the eigenstate thermalization hypothesis (ETH) may be introduced as an extension of the random matrix theory, physical Hamiltonians and observables differ from random operators. One of the challenges is to embed local integrals of motion (LIOMs) within the ETH. Here we make steps towards a unified treatment of the ETH in integrable and nonintegrable models with translational invariance. Specifically, we focus on the impact of LIOMs on fluctuations and structure of the diagonal matrix elements of local observables We first show that nonvanishing fluctuations entail the presence of LIOMs. Then we introduce a generic protocol to construct observables, subtracted by their projections on LIOMs as well as products of LIOMs. The protocol systematically reduces fluctuations and/or the structure of the diagonal matrix elements. We verify our arguments by numerical results for integrable and nonintegrable models

Superconductivity intertwined with charge order in a transition metal dichalcogenide

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In correlated systems, superconductivity (SC) is often intertwined with insulating spin or charge orders. Charge density waves (CDW) allow for the special case of such cooperation: SC could emerge in conducting domain walls that appear upon CDW suppression by pressure, chemical substition or doping. Indeed, there is extensive experimental evidence that the SC onset is correlated with the appearance of the CDW domain walls in the transition metal dichalcogenides, with most notable and well-studied cases of 1*T*-TaS_2 [1] and 1*T*-$TiSe_2$ [2]. The role of domain walls in 1*T*-TaS_2 was challenged in the recent spectroscopic studies [3-5] that revealed the lack of metallicity in the stand-alone walls. Even more surprising is that SC has not been observed so far in the conducting domain-like photoinduced metastable state in 1*T*-TaS_2 [5, 6]. The problem is that the key component of the picture – correlating the superconducting gap to the charge order – is missing.

In the first part of my talk I will present the spectroscopic imaging scanning tunneling microscopy of the superconducting 1*T*-TaSSe close to the optimal doping performed below and above T_c~3.5K. It clearly shows the correlation of the superconducting gap size with the local charge order, but both are essentially disentangled from the CDW domain structure.

In the second part, I will provide the comparison of the spectroscopic data for the Se-substituted superconducting sample with that for a variety of charge configurations [7] in the pristine 1*T*-TaS_2 and discuss the possible pathways for metastable superconductivity.

This work was supported by ARRS, P1-0040 and ERC ADG GA 320602 Trajectory.

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Superconductivity emerging upon Se doping of a quantum spin liquid 1T-TaS_2

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Layered 1*T*-TaS_2 has recently emerged as a surprising candidate for a quantum spin liquid on a simple triagonal lattice. Here we report on a detailed ^{77}Se nuclear magnetic resonance and ^{181}Ta nuclear quadrupole resonance study of Se-doped 1*T*-TaS_2. The data shows a remarkable robustness of a quantum spin liquid at low Se doping levels despite the growing importance of disorder effects. A dramatic change in the low-energy electronic excitations are observed in samples with Se content higher than 15% where Mott insulating state gives way to correlated metal and low-temperature superconductivity. The effects of antiferromagnetic correlations can be clearly seen in the normal state above the superconducting critical temperature $T_c = 3.5$ K and together with the underlying disorder may account for a large superconducting gap-to-T_c ratio $2\Delta/k_B T_c \approx 7$ deduced from scanning tunneling microscopy.

Universal properties of quantum spin-liquid models

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There are several prototype planar quantum spin models which are investigated in connection with possible spin-liquid ground state. Among most studied are isotropic S=1/2 extended J_1-J_2 Heisenberg models on kagome, triangular and square lattices, as well as the Heisenberg model with ring exchange, whereby their universal properties have been not pointed out so far. The reduced-basis approach gives a clear indication on the similarity of thermodynamic quantities on kagome and triangular lattice in their spin-liquid regimes [3]. We further show by using extensive numerical calculations of entropy and uniform susceptibility, that in all considered models the thermodynamic quantities are quite universal [4]. The hallmark of spin-liquid regimes, also in other considered models, is the vanishing Wilson ratio at low temperatures, indicating the predominant role of low-lying singlet excitations over the triplet ones. This is in contrast to reference one-dimensional Heisenberg model and the popular spinon Fermi- surface concept. Since thermodynamic quantities are measured also in real spin-liquid materials, we present a comparison with experimental results for a quantum kagome system, which, however, requires to take into account also the Dzyaloshinskii-Moriya interaction.

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Temperature and fluence dependent transient reflectivity study of the insulator–metal transition in $CuIr_2S_4$

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The spinel-structure compound $CuIr_2S_4$ shows unusual, presumably orbitally-driven, three-dimensional Peierls-like metal-insulator transition at 230 K [1]. The transition is accompanied by a long-range charge ordering forming Ir dimers [2] and a strong decrease of the magnetic susceptibility [3]. $CuIr_2S_4$ is especially interesting due to the exhistence of the low temperature X-ray and visible-light-induced disordered conducting phase [4] with persistent dimerization and supressed long-range order [5]. At low T the presence of short-range incommensurate structural correlations was observed [6] in the X-ray induced conducting phase suggesting presence of competing instabilities that appear after the suppression of the insulating phase. Motivated by the possibility of inducing an ultrafast insulator-metal transition to a meta-stable conducting state by a single femtosecond optical pulse in another system with competing instabilities [7] we performed a systematic investigation of the electronic relaxation dynamics and coherent phonon response using ultrafast transient reflectivity in $CuIr_2S_4$ single crystals as a function of temperature and excitation fluence.

We find that the transient reflectivity in the low-temperature insulating phase at 1.55 eV photon energy is dominated by the broken-lattice-symmetry-induced coherent lattice response which abruptly vanishes at the insulator-metal transition.

At strong excitation, the low-temperature insulating phase is suppressed on a picosecond timescale above the threshold excitation fluence which is around 2 mJ/cm^2. The observed coherent phonon frequency shifts indicate that, at the threshold fluence, the lattice degrees of freedom are heated close to the equilibrium insulator-metal transition temperature.

The nonlinearities in the transient reflectivity observed at a significantly lower fluence suggest that above fluences of around 0.3 mJ/cm^2 the charge order is decoupled from the lattice and transiently suppressed on a short timesale.

Upon femtosecond photoexcitation with 1.55 eV photon energy we haven't found at any signature of a long lived metastable state. However, the presence of the disordered conducting phase upon ultrafast optical excitation is not completely ruled out and further photoconductivity experiments are necessary for resolving the issue.

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Many-body localization in a dense interacting quantum system

G. Aeppli

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We describe optical and magnetic susceptibility measurements on the isostructural dilution series $LiHo_pY_{1-p}F_4$ which represents a random atomic trap for magnetic Ho atoms. When p=0.045, the low temperature state depends on the strength of thermal bath coupling. For strong coupling, a conventional spin glass is achieved, whereas for weak coupling, a random singlet state is stabilized. The latter exhibits many-body localization, as established using spectral hole burning.

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Characterization of photoexcited states in the half-filled one-dimensional extended Hubbard model assisted by machine learning

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Nonequilibrium processes in strongly correlated electron systems can provide new insights into the dynamical properties of these systems, which can be qualitatively different from their weakly interacting counterparts. One such example is nonequilibrium induced phase transition. As the system is driven away from the equilibrium, under certain conditions, a crossover from one state to another metastable state may occur. Such an indication has been reported theoretically in the half-field one-dimensional extended Hubbard model (1DEHM) [1], where by tuning the laser frequency and strength a sustainable charge order enhancement is found when the system is originally in the spin-density-wave (SDW) phase but close to the transition to charge-density wave (CDW). However, the detailed nature of the photoexcited state over full parameter space is still unclear. To characterize the photoexcited states in the 1DEHM, we apply supervised machine learning [2]. We use the following procedure. Firstly, using density-matrix renormalization group (DMRG), we calculate the ground state of 1DEHM with correlated hopping terms that are suggested from the Floquet time-independent effective model of a driven Hubbard model. We next prepare entanglement spectrum (ES) for the possible ground states with SDW, CDW, bond-charge-density wave (BCDW), and bond-spin-density wave (BSDW). Using these ES, we construct neural network with four layers [3]. Finally, we use the neural network to judge the ES of photoexcitaed wave functions of the 1DEHM. Predicted phases are checked by time-dependent local and non-local correlation functions obtained by time-dependent DMRG. Using this procedure, we predict a possible BSDW for the photo-driven 1DEHM in a region of the CDW ground state and confirm this by calculating the various time-dependent correlation functions.

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Thermal effects on a non-adiabatic spin-flip protocol of spin-orbit qubits

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Jožef Stefan Institute, Department of theoretical physics, Ljubljana, Slovenia

We study the influence of a thermal environment on a non-adiabatic spin-flip driving protocol of spin-orbit qubits. The driving protocol operates by moving the qubit, trapped in a harmonic potential, along a nanowire in the presence of a time-dependent spin-orbit interaction [1]. We consider the harmonic degrees of freedom to be weakly coupled to a thermal bath. We find analytical expressions for the Floquet states and derive the Lindblad equation for a strongly driven qubit. The Lindblad equation corrects the dynamics of an isolated qubit with Lamb shift terms and dissipative behaviour. We find that the Lamb shift introduces slow frequencies into the system which allows for optimization of the driving protocol in order to minimize the dissipative effects [2].

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Quantum spectroscopy for quantum materials

D.Fausti

Time Resolved X-Ray Spectroscopies, Elettra - Sincrotrone Trieste S.C.p.A.

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 temperature. In this presentation I will start reviewing our most recent results in archetypal strongly correlated cuprate superconductors revealing, once more, that we need new spectroscopic tools to address fluctuations in quantum materials and introduce our new approach to go beyond mean photon number observables. In this framework, we have demonstrated in different settings that photonic fluctuations (of both classical and quantum nature) provide a unique and powerful asset to address fluctuations in materials and contain viable spectroscopic information. In details, in the presentation I will focus on time domain covariance spectroscopies, i.e. an approach we recently developed to exploit multimode classical correlations in stochastic light pulses to unveil the non-linear response in complex matter. I Will start discussing measurements using ultra-short stochastic pulses characterized by spectrally uncorrelated intensity (and phase) fluctuations. In this limit, each repetition of the experiment can be considered as a measurement under new conditions and, as we demonstrated, the Raman response in the sample can be retrieved by measuring the spectral correlations in different pulses which are produced by Impulsive Stimulated Raman Scattering (ISRS). I will show how femtosecond covariance spectroscopy can be extended to time domain measurements of coherent vibrational responses in matter and to multimode correlations of quantum nature.

Ergodicity breaking in chaotic systems

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I will introduce a class of spin ladder models that is in general chaotic, can be disordered, and includes the integrable Hubbard chain as a special case. Nevertheless, one can analytically show the existence of exponentially many atypical eigenstates that are populated by noninteracting excitations. Depending on parameters they can e.g. exhibit Anderson localization, or, surprisingly, ballistic transport at any disorder strength. These properties differ strikingly from those of typical eigenstates nearby in energy which give rise to diffusion. Results have implications for possible localization in the presence of non-Abelian symmetries, as well as for recent interest in states avoiding thermalization.

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Configurational Tunnelling on a Programmable Quantum Annealer

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Quantum computing has attracted a lot of attention in recent years, the latest example being Google's controversial claim of achieving quantum supremacy [1]. Quantum computers offer the potential for solving quantum mechanical problems which are nearly impossible to solve by contemporary classical computers [2]. In the work presented here, we investigate the problem of configurational tunneling in the material system 1*T*-TaS_2. At low temperatures, the system exhibits strongly correlated behavior in the form of repulsive polarons on an underlying atomic lattice [3–7]. Using a charged lattice gas model, Monte Carlo simulations find a stable regularly ordered polaronic crystal at the ratio of polarons to lattice sites 1/13, which is observed as the commensurate charge density wave in 1T-TaS_2. Upon doping, a multitude of near-degenerate domain wall configurations appear which accommodate the doped charges. The effective degeneracy of configurational states subject to quantum fluctuations may lead to a quantum *charge* liquid at low temperatures, analogous to the canonical quantum spin liquid. In our work we attempt to simulate the charged lattice gas model of polarons on a programmable quantum annealer provided by the D-Wave company. Using the reverse anneal feature we investigate the possibility of tunneling from one domain wall configuration to another. This is directly applicable to recent measurements in 1*T*-TaS_2, where configurational reordering has been observed, which can be attributed to quantum tunneling. Simulating configurational tunneling of a strongly correlated system on such a scale presents an important step forward in the application of quantum computing to real world problems.

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Charge configuration memory devices

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Superconducting computer systems and quantum computers represent the next step in both performance and efficiency boost compared to classical computers based on silicon technology. One of the main factors limiting their progress is the absence of a low energy, ultrafast, durable and non-volatile memory device which also works at low temperatures. Charge configuration memory (CCM) device presented here combines all these attributes while also having the advantage of being uncomplicated in its design and thus scalable and integrable into bigger computer systems.

We present a CCM device based on $1T$-TaS_2 which relies on switching between different topologically protected electronic states to store information. Scanning tunnelling microscopy (STM) measurements expose the microscopic changes in the electronic landscape during the device operation and show topological defects responsible for the non-volatility of the device.

We also demonstrate device operation to temperatures as low as 250K and the endurance of the device up to 10^7 write-erase cycles.

The work was supported by ERC ADG Trajectory (GA320602), ERC PoC Umem4QC and the Slovenian Research Agency (young researcher, P10040)

Drafting the Science Case for Ultrafast Laser-based experiments with EUV Soft X-Ray Photons

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Starting from the archetypal FERMI externally seeded FEL, recent theoretical and experimental progress has shown the possibility of producing fully coherent, variable polarization and tunable, Soft-X-ray, ultra-short pulses at high repetition rate.

This ultimate achievement will unlock the gate for performing X- ray based experiments that are qualitatively different from those available at any current or planned X-ray source. Here we will review the experiments and the ideas that represent the science frontier in soft X-ray, time-resolved spectroscopy, coherent imaging and Xray coherent optics non equilibrium spectroscopy. These studies will lead to an understanding of fundamental dynamics, occurring on the ultrafast time and nanometer spatial scales, needed for addressing a broad range of science essential for resolving our complex and long-term energy challenges, environmentally urgent questions and demanding problems in bioscience and novel materials.

Probing local magnetic and lattice correlations with femtosecond RIXS

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Resonant Inelastic X-ray Scattering (RIXS) has become a versatile tool for probing quantum materials, allowing simultaneous access to charge, lattice, magnetic and orbital degrees of freedom [1]. Much of its success in recent years has been driven by huge improvements in instrumentation, and with the recent advent of X-ray free electron lasers such as the LCLS, it has become possible to translate this technique into the time-domain. Given its ability to address multiple degrees of freedom at once, trRIXS therefore has huge potential for investigating materials with cooperative dynamics. Nevertheless, it remains technically very challenging to perform such experiments. We perform trRIXS measurements at the oxygen K-edge in order to probe spin correlation dynamics in the model spin-frustrated system $CuGeO_3$. This quasi-1D material formed of chains of edge-sharing CuO4 plaquettes displays pronounced anti-ferromagnetic (AFM) nearest-neighbour spin correlations, and transitions into a spin-Peierls phase below 14 K, highlighting a close relation between magnetic and lattice sub-systems. As a result of these AFM correlations a Zhang-Rice singlet (ZRS) exciton can develop during the RIXS process, resulting in a distinct energy loss peak close to the charge transfer gap [2]. The amplitude of this ZRS exciton directly reflects the nearest-neighbour AFM correlations, and can therefore be used as a local probe to access the dynamics of the magnetic correlations and how they are influenced by other degrees of freedom in the solid. By photoexciting $CuGeO_3$ across the charge gap (~4 eV) we induce a sudden reduction of the intensity of the ZRS exciton within 1 ps, which rapidly recovers before gradually decreasing again towards a stable value after ~10 ps. Comparison to equilibrium measurements and a thermal model reveal that the longer time scale dynamics are dominated by heating of the lattice. However, the initial drop and recovery of the ZRS at short time scales clearly implies non-thermal behaviour. By comparison with a simple 1D model we reveal the origin of this fast, non-thermal behaviour, which can be understood as the influence of coherent lattice motion on the local AFM exchange coupling. We therefore highlight that trRIXS can be used to probe local magentic dynamics, a quantity inaccessible to other techniques.

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Melting of charge-density-wave states in the 1D Holstein model

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[4] *Department of Physics and Astronomy, The University of Tennessee, Knoxville, USA*
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We investigate the real-time dynamics in the half-filled, one-dimensional Holstein model by starting from a range of initial conditions. These include charge-density wave (CDW) states of undressed electrons, of small polarons and quantum quenches between the CDW and the Luttinger-liquid phase. We employ a recently developed density-matrix renormalization group method (DMRG-LBO) that treats the phononic Hilbert space efficiently by a local basis optimization [2]. In this talk, I will present the first application of the DMRG-LBO to finite electron densities. We also developed a DMRG algorithm for an efficient ground-state search based on LBO. I will introduce these methods and then focus on the temporal decay of the CDW order parameter depending on initial conditions and the post-quench parameters that put the system into the Luttinger-liquid or into the CDW phase (see also [3]). We observe very different short time dynamics for which we propose intuitive explanations.

This research was supported by the DFG (Deutsche Forschungsgemeinschaft) via Resarch Unit FOR 1807 and CRC 1073.

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Block-Spiral Magnetism: A New Type of Frustrated Order

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Competing interactions in Quantum Materials induce novel states of matter such as frustrated magnets, an extensive field of research both from the theoretical and experimental perspectives. Here, we show that competing energy scales present in the low-dimensional orbital-selective Mott phase (OSMP) induce an exotic magnetic order, never reported before. Earlier neutron scattering experiments on iron-based 123 ladder materials, where OSMP is relevant, already confirmed our previous theoretical prediction of block-magnetism (magnetic order of the form ↑↑↓↓). Now we argue that another novel phase can be stabilized in multiorbital Hubbard models, the "block-spiral state". In this state, the magnetic islands form a spiral propagating through the chain but with the blocks maintaining their identity, namely rigidly rotating. This new spiral state is stabilized without any apparent frustration, the common avenue to generate spiral arrangements in multiferroics. By examining the behaviour of the electronic degrees of freedom, parity breaking quasiparticles are revealed. Finally, a simple phenomenological model that accurately captures the macroscopic spin spiral arrangement is also introduced

Weak Ergodicity Breaking and Many-Body Scars in Constrained Quantum Systems

Zlatko Papić

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Recent experiments on large chains of Rydberg atoms [H. Bernien et al., Nature 551, 579 (2017)] have demonstrated the possibility of realizing 1D quantum simulators with locally constrained Hilbert spaces. These experiments have revealed surprising signatures of non-ergodic dynamics in an apparently thermalizing quantum system, for example manifested as persistent oscillations following a quench from the initial Neel state of atoms. In this talk 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 [C. J. Turner, A. A. Michailidis, D. A. Abanin, M. Serbyn, Z. Papić, Nat. Phys, 14, 745 (2018)]. The special states are analogues of unstable classical periodic orbits in the single-particle quantum billiards [E. J. Heller, Phys. Rev. Lett. 53, 1515 (1984)]. I will present a model based on a single particle hopping on the Hilbert space graph, which quantitatively captures the scarred wave functions in large systems that can be numerically simulated.

These results suggest that scarred many-body bands give rise to a new universality class of quantum dynamics, which is distinct from thermalization or localization, that could be used for creating and manipulating novel states with long-lived coherence in systems that are now available in experiments.

Spectral features of generic open quantum many-body systems

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[2] *Stanford University, USA*

In this talk, I will discuss spectral properties of generic open quantum many-body systems from two perspectives.

The first part will discuss the spectra of ergodic many-body Hamiltonians, with a small non-Hermitian component [1]. In such systems, the interactions induce a nontrivial topology of the spectrum, due to an exponential-in-system-size proliferation of exceptional points which have the Hermitian limit as an accumulation (hyper)surface. The nearest-neighbor level repulsion characterizing Hermitian ergodic many-body systems is thus shown to be a projection of a richer phenomenology, where actually all the exponentially many eigenvalues are pairwise connected in a topologically robust fashion via exceptional points.

In the second part of the talk, I will discuss the spectra of purely dissipative Liouvillians with a notion of locality, where we find a sharp separation of the relaxation timescales according to the locality of observables [2]. The spectrum is composed of several dense clusters with random matrix spacing statistics, each featuring a lemon-shaped support wherein all eigenvectors correspond to n-body decay modes. This implies a hierarchy of relaxation timescales of n-body observables, which we verify to be robust in the thermodynamic limit.

[1] D. J. Luitz and F. Piazza “Exceptional points and the topology of quantum many-body spectra” Phys. Rev. Research **1**, 033051 (2019), arXiv:1906.02224
[2] K. Wang, F. Piazza, D. J. Luitz” Hierarchy of relaxation timescales in local random Liouvillians “ arXiv:1911.05740

Quantum chaos challenges many-body localization

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Characterizing states of matter through the lens of their ergodic properties is a fascinating new direction of research. In the quantum realm, the many-body localization (MBL)[1, 2] was proposed to be the paradigmatic nonergodic phenomenon, which extends the concept of Anderson localization[3] to interacting systems. At the same time, random matrix theory has established a powerful framework for characterizing the onset of quantum chaos and ergodicity (or the absence thereof) in quantum many-body systems.[4] Here[5] we study a paradigmatic class of models that are expected to exhibit MBL, i.e., disordered spin chains with Heisenberg-like interactions. Surprisingly, we observe that exact calculations show no evidence of approaching MBL while increasing disordered strength in the ergodic regime. Moreover, a scaling analysis suggests that quantum chaotic properties survive for any disorder strength in the thermodynamic limit. Our results are based on calculations of the spectral form factor, which provides a powerful measure for the emergence of many-body quantum chaos.

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Tuesday, December 17th

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Exact Correlation Functions in Nonintegrable Lattice Models in 1+1 Dimension

T. Prosen

Tackling quantum many-body dynamics by typicality, numerical linked cluster expansions, and projection operator techniques

R. Steinigeweg

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In my talk, I demonstrate that dynamical quantum typicality (DQT) is a versatile approach to quantum many-body systems out of equilibrium and can be combined with other numerical and analytical approaches to real-time evolution in integrable and nonintegrable models. I particularly discuss the idea of combining DQT with (i) numerical linked cluster expansions [1,2] and (ii) projection operator techniques [2,3]. As a specific example, I apply these ideas to the decay of current-current correlation functions in spin-1/2 Heisenberg ladders in the entire range from weak to strong rung couplings.

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Time-Resolved VUV ARPES at 10.8 eV photon energy and MHz repetition rate

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The quest for mapping the femtosecond dynamics of the electronic band structure of complex materials over their full first Brillouin zone is pushing the development of schemes to efficiently generate ultrashort photon pulses in the VUV energy range. At present, the critical aspect in Time- and Angle-Resolved Photoelectron Spectroscopy (TR-ARPES) is to combine a high photon energy with high photoemission count rates and a narrow pulse-bandwidth, necessary to achieve high energy resolution, while preserving a good time resolution and mitigating space-charge effects. Here we show a novel approach to produce light pulses at 10.8 eV, combining high repetition rate operation (1-4 MHz), high energy resolution (∽26 meV) and space-charge free operation, with a time-resolution of ∽700 fs. These results have been achieved by generating the ninth harmonic of a Yb fiber laser, through a phase-matched process of third harmonic generation in Xenon of the laser third harmonic.

The full up-conversion process is driven by a seed pulse energy as low as 10 μJ, hence is easily scalable to multi-MHz operation. This source opens the way to TR-ARPES experiments for the investigation of the electron dynamics over the full first Brillouin zone of most complex materials, with unprecedented energy and momentum resolutions and high count rates. The performances of the setup are tested by TR-ARPES on the topological insulator Bi_2Se_3.

Polarization-resolved broadband time-resolved optical spectroscopy for complex materials: application to the case of $MoTe_2$ polytypes

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Time-resolved optical spectroscopy (TR-OS) has emerged as a fundamental spectroscopic tool for probing complex materials, to both investigate ground-state-related properties and trigger phase transitions among different states with peculiar electronic and lattice structures. We describe a versatile approach to perform polarization-resolved TR-OS measurements, by combining broadband detection with the capability to simultaneously probe two orthogonal polarization states. This method allows to probe, with femtoseconds resolution, the frequency-resolved reflectivity or transmittivity variations along two mutually orthogonal directions, matching the principal axis of the crystal structure of the material under scrutiny. We report on the results obtained by acquiring the polarization-dependent transient reflectivity of two polytypes of the $MoTe_2$ compound, with 2*H* and 1*T*' crystal structures. We reveal marked anisotropies in the time-resolved reflectivity signal of 1*T*'-$MoTe_2$, which are connected to the crystal structure of the compound. Polarization- and time- resolved spectroscopic measurements can thus provide information about the nature and dynamics of both the electronic and crystal lattice subsystems, advancing the comprehension of their inter-dependence in particular in the case of photoinduced phase transitions; in addition, they provide a broadband measurement of transient polarization rotations.

Photoinduced electronic textured phase in the correlated oxide Mo_8O_{23}

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»Hidden« phases that are absent on equilibrium phase diagrams can be induced and stabilized in some correlated materials by a single ultrashort, femtosecond-scale pulse [1,2]. The driving forces behind the photoinduced switching to a »hidden phase« are actively debated, and delicate balance between localized and itinerant electrons may play the important role.

Here we discuss photoinduced electronic textured phase in molybdenum suboxide Mo_8O_{23}. In this compound, mutliple correlated orders compete already in the ground state, with the gap in the density of states fully developing below ~ 60 K, that is hundreds of Kelvins below structural transitions that occur at 350 K and 285 K [3,4]. We show that a single femtosecond pulse can stabilize a distinct phase with the same Low-T structure yet much wider charge gap, that survives up to 350 K. We discuss how possible competition of the ground orders could be related to the electronic texture observed in tunneling spectroscopy and how the photoinduced doping may affect this competition.

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[3] V. Nasretdinova et al. Phys.Rev. B 99, 085101 (2019)
[4] V. Nasretdinova et al. Sci. Rep. 9, 15959 (2019)

Carrier relaxation dynamics in Kondo insulator YbB_{12}

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We investigate the photoexcited quasiparticle relaxation dynamics in a Kondo insulator YbB_{12} by means of time resolved all-optical pump-probe spectroscopy. In particular, we focus on the temperature and excitation density dependent dynamics to address the temperature dependent changes in the low energy electron structure associated with the interplay/hybridization between the Yb 4f-levels and the conduction band electrons [1,2]. At low temperatures, both the rise-time and recovery of the photoinduced reflectivity changes show dramatic temperature and excitation density dependence. The results are well accounted by the presence of the 20 meV indirect hybridization gap [2]. Both, the dependence of build-up and its recovery on excitation density can be in detail accounted for by the phenomenological Rothwarf-Taylor model, describing the carrier relaxation across the narrow electronic hybridization gap [3-6], bottlenecked by the re-absorption of emitted phonons with energy larger than the gap.

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[6] K. S. Burch, E.E.M. Chia, D. Talbayev, B.C. Sales, D. Mandrus, A. J. Taylor, and R. D. Averitt, Phys. Rev. Lett. **100**, 026409 (2008)

Topologically protected gap in magnetic Weyl semimetal $Co_3Sn_2S_2$

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Weyl semimetals exhibit topologically protected chiralities, which enlighten future applications ranging from low dissipation electronics, spintronics, photonics, to quantum computation. However, opening and tuning gaps that preserve topological properties have rarely been reported so far, which impedes the implementation of practical devices. Here we report an unconventional type of gap in a magnetic Weyl semimetal (MWSM) $Co_3Sn_2S_2$, which is associated with temperature-driven Weyl node annihilation (WNA) and exhibits a temperature dependence converse to those of most previously known gaps. By observing time-resolved ultrafast dynamics, we uncover that the gaps open at the merged Weyl nodes, starting from T_{WNA} = 131.5 K and reaching the maximum Δ^* = 7.9 meV at T^* = 225 K, through a temperature-driven topological phase transition. Significantly, our spin-resolved ultrafast dynamics results demonstrate that the excited quantum states nearby the gaps preserve topologically protected spin-polarized photocarriers. Our investigation endows new application potentials for topological materials and sheds new light on exploring the topological properties from the excited state perspective.

Symmetry Enforced Dirac Points in Antiferromagnetic Semiconductors

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It is shown that the symmetry enforced Dirac points exist at some time reversal symmetric momenta in antiferroemgnetic compound GdB_4. These Dirac points may be controlled by the external magnetic field or by the deformation of the crystal. Application of the external magnetic field leads to splitting of these points into Weyl points or to opening of a gap depending on the field direction. The application of the symmetry breaking deformation also opens a gap in the spectrum. Suppression of the antiferromagnetic order leads to the formation of the nodal line instead of the Dirac points. This indicates that the symmetry enforced Dirac semimetals may be effectively used in different spintronic devices.

Entanglement and Matrix Elements of Observables in Interacting Integrable Systems

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Interacting integrable systems in one dimension represent a special class of experimentally relevant systems, which still remain less understood. On the one hand, interactions are present in those systems as in generic, nonintegrable, systems (making their study challenging), and on the other hand, they exhibit extensive numbers of local conserved quantities as noninteracting systems do. The presence of such conserved quantities precludes thermalization in integrable (noninteracting and interacting) quantum systems. In my talk I will focus on the bipartite von Neumann entanglement entropy and matrix elements of local operators in the eigenstates of an interacting integrable Hamiltonian (the paradigmatic spin-1/2 XXZ chain), and contrast their behavior with that of generic systems [1]. I will first argue that our results establish the entanglement entropy as a powerful measure to distinguish integrable models from generic ones. Then, I will study the off-diagonal matrix elements of local observables. Our results show that their variance scales identically to the variance in generic systems, i.e., it is proportional to the inverse Hilbert space dimension for properly normalized obsevables [2]. On the other hand, we find that the distribution of offdiagonal matrix elements is nearly log-normal in interacting integrable systems, in contrast to the Gaussian distribution in generic systems.

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Thermodynamic uncertainty relations from exchange fluctuation theorems

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Thermodynamic uncertainty relations (TURs) place strict bounds on the fluctuations of thermodynamic quantities in terms of the associated entropy production. In this work we identify the tightest (and saturable) matrix-valued TUR that can be derived from the exchange fluctuation theorems describing the statistics of heat and particle flow between multiple systems of arbitrary dimensions. Our result holds for both quantum and classical systems, undergoing general finite-time, non-stationary processes. Moreover, it provides bounds not only for the variances, but also for the correlations between thermodynamic quantities. To demonstrate the relevance of TURs to the design of nanoscale machines, we consider the operation of a two-qubit SWAP engine undergoing an Otto cycle and show how our results can be used to place strict bounds on the correlations between heat and work.

The Bethe-Salpeter Equation at the critical end-point of the Mott transition

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Strong repulsive interactions between electrons can lead to a Mott metal-insulator transition, described theoretically by the Dynamical Mean-Field Theory (DMFT). We reconsider the critical end point of the metal-insulator transition, the quintessential part of the DMFT phase diagram, on the two-particle level. A divergence of the Bethe-Salpeter equation occurs which simultaneously explains the behavior of the compressibility, the hysteresis region and the iterative stability of the DMFT equations.

Dynamics of MgB_2 superconductor driven by narrow-band THz pulses

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We report on systematic studies of the superconducting state suppression and recovery dynamics in a two-gap superconductor MgB_2 driven by narrow band THz pulses. The dynamics is studied as a function of the pump photon energy, tuned between the two superconducting gap frequencies, temperature and excitation density. The superconducting state recovery dynamics is found to be temperature and excitation density dependent, very similar to the previous studies on a conventional BCS superconductor NbN [1] or the high-Tc superconductor PCCO [2]. The THz driven pair-breaking dynamics, which was found to be resolution limited in the previous experiments using narrow-band THz pumping on NbN [1] and PCCO [2], is however found to depend on temperature and excitation photon energy in MgB_2.

Recent study of narrow-band THz pumping of NbN superconductor provided evidence for THz driven enhancement effects on superconductivity, competing with the common pair-breaking driven collapse of superconductivity [1]. This was attributed to the THz driven excitation of thermally excited quasiparticle away from the gap edge, resulting in a highly non-thermal distribution function population and enhancement of superconductivity within the Eliashberg scenario [3]. Study of the temperature dependence of relative gap suppression for constant excitation density suggests similar effects in MgB_2, which are particularly pronounced at temperatures close to T_c and for weak excitation densities.

Finally, we report on first results of third harmonic generation experiments in relation to the collective Higgs and Legget modes of MgB_2.

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[3] G. M. Eliashberg et al., J. Low Temp. Phys. **10**, 449 (1973)

Ultrafast electronic and structural dynamics in an excitonic insulator

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Ultrafast control of matter phases is of both fundamental and technological interest. Here, we study the ultrafast electronic and structural dynamics of Ta_2NiSe_5 by means of time- and angleresolved photoelectron spectroscopy (trARPES) [1] and transient mid-IR reflectivity measurements [2]. Ta_2NiSe_5 was proposed to undergo a semiconductor-to-excitonic-insulator (EI) phase transition below $T_c \approx 328$ K, combined with a structural change from an orthorhombic to a monoclinic symmetry [3]. Such an EI phase is expected to occur in smallband-gap semiconductors with strong electron-hole interaction as excitons can form spontaneously and condense into a ground state at a sufficiently low temperature [4].

Below T_c, trARPES shows a strong fluence-dependent depopulation of the valence band at Γ, until the optical absorption saturates at a critical pump fluence $F_{sat} = 0.2$ mJ cm^{-2}. This is reflected in a saturation of the mid-IR optical response at F_{sat}. Particularly, two coherent optical phonons at 2.1 and 4.0 THz, markers of the EI/monoclinic phase, persist above F_{sat}, indicating that the photoinduced structural phase transition is hindered by optical absorption saturation.

Upon tuning of the pump fluence, the electronic band gap can be either reduced or increased on an ultrafast timescale. Below F_{sat}, trARPES of both the occupied and unoccupied electronic band structure reveals a band gap shrinking due to photocarrier-induced screening of the Coulomb interaction. These dynamics are analogous to the behavior of a photoexcited semiconductor (photoinduced band gap renormalization). Conversely, above F_{sat}, trARPES of the valence band top at Γ indicates a band gap widening that persists up to approximately 1 ps. We find that this nontrivial out-of-equilibrium widening originates from the interplay of transient screening of the Coulomb interaction and photoenhancement of the EI condensate density, supported by theoretical calculations. Thus, our results prove it is possible to optically manipulate an exciton condensate and gain ultrafast control of its electronic band gap.

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Wednesday, December 18th

	Chair: J. Mravlje	
9:00 - 9:25	**R. Žitko**: Yu-Shiba-Rusinov states in multi-impurity Kondo systems	58
9:25 - 9:50	**P. Kos:** Chaotic Quantum Circuits	59
9:50 - 10:15	**J. Bonča:** Spectral function of the holstein polaron at finite temperature	60
10:15 - 10:45	*Coffee break*	
	Chair: Y. Gerasimenko	
10:45 - 11:10	**J. Mravlje:** Electron-electron scattering and electron-lattice scattering effects on transport in Fe under extreme conditions in the Earth's core	61
11:10 - 11:25	**G. Jecl**: Photoinduced dynamics of the low-temperature charge order in $IrTe_2$	62
11:25-11:40	*Closing*	

Yu-Shiba-Rusinov states in multi-impurity Kondo systems

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A chain of magnetic impurities coupled to a superconductor can be tuned to a topological phase with Majorana end modes. Systems of this type have been proposed as potential building blocks of topological quantum computers. Possible experimental realisations are hybrid semiconductor-superconductor devices made out of nanowires in contact with superconducting contacts and magnetic adsorbates on surfaces of superconducting substrates. I will discuss recent combined experimental and theoretical studies of these systems: double quantum dots electrostatically defined in nanowires [1,2] and clusters of Fe atoms on the surface of Ta [3]. Both can be modelled using the two-impurity Kondo model with BCS continuum that can be solved using the numerical renormalization group. The cross-over between the local singlet and the Kondo singlet regimes manifests through the characteristic behavior of sub-gap Yu-Shiba-Rusinov states. This work establishes that the exchange interaction plays a key role in the physics of Shiba states and that a modelling in terms of quantum impurities is necessary for a correct description of sub-gap spectra.

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[2] J. C. Estrada Saldana et al., arXiv:1812.09303
[3] A. Kamlapure et al., arXiv: 1911.03794

Chaotic Quantum Circuits

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One of the simplest formulations of many-body quantum dynamics is in the form of a quantum circuit. This is currently attracting a lot of attention from different subfields. First context is that of quantum computation and simulation. Secondly, it is useful for understanding chaotic quantum dynamics, for instance in the context of random unitary circuits. In my talk I will present quantum circuits with a special property, called dual-unitarity, which means that the evolution propagator in the space direction is also unitary. Remarkably, this property allows for an exact solution of the dynamical correlation functions. We can use it to characterize the dual-unitarity spin one-half circuits. Furthermore, to investigate the complexity of the dynamics, I will discuss the evolution of the operator entanglement entropy.

[1] B. Bertini, P. Kos and T. Prosen arXiv:1904.02140 (2019)
[2] B. Bertini, P. Kos and T. Prosen arXiv:1909.07407 (2019)

Spectral Function of the Holstein Polaron at Finite Temperature

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I will present the Holstein polaron spectral function on a one dimensional ring obtained using the finite–temperature (T) Lanczos method. With increasing T additional features in the spectral function emerge even at temperatures below the phonon frequency. We observe a substantial spread of the spectral weight towards lower frequencies and the broadening of the quasiparticle (QP) peak. In the weak coupling regime, the QP peak merges with the continuum in the High-T limit. In the strong coupling regime, the main features of the low–T spectral function remain detectable up to the highest T used in our calculations. The effective polaron mass shows a non–monotonic behavior as a function of T at small phonon frequency but increases with T at larger frequencies. The self energy remains k-independent even at elevated T in the frequency range corresponding to the polaron band while at higher frequencies it develops a distinguishable k-dependence. Analytical expressions for the first few frequency moments are derived and they agree well with those extracted from numerical calculations in a Wide-T regime.

[1] J. Bonča, S. A. Trugman, and M. Berciu, Phys. Rev. **B 100**, 094307 (2019)

Electron-electron scattering and electron-lattice scattering effects on transport in Fe under extreme conditions in the Earth's core

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We report resistivity and thermal conductivity of Fe under conditions that occur in the Earth's core. The influences of electron-lattice and electron-electron scattering as well as their interplay are all considered. The implications of the results for transport in strongly thermally disordered metals as well as the geophysical implications for the geodynamo are discussed.

Photoinduced dynamics of the low-temperature charge order in $IrTe_2$

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$IrTe_2$ is a quasi-2D layered material which exhibits a structural transition at T_{C1} = 275 K from a high temperature (HT) hexagonal phase to a monoclinic low temperature (LT1) phase which is accompanied by the appearance of stripe order. A second transition into an LT2 phase occurs at T_{C2} = 180 K in which the dominant periodicity of the stripe phase changes [1]. Superconductivity can be introduced below 3.1 K by doping with Pt or Pd [2] or in undoped samples at surface patch domains of hexagonal symmetry which can form at intersections of three differently oriented stripe phases [3]. We have investigated the dynamics of all three phases on sub-picosecond timescales by means of ultrafast optical spectroscopy and have characterized the transient reflectivity relaxation and its anisotropy in a temperature range between 8 and 295 K. Additionally, by employing scanning tunnelling microscopy (STM) and imaging the surface after high fluence photoexcitation we have investigated the degree to which the stripe phase can be controlled by ultrafast optical pules on long (hundreds of seconds) timescales. At low photoexcitation fluences the transient reflectivity response of the LT2 scales roughly linearly with fluence. At higher fluences a transition to the HT phase can be inferred from a change in the relaxation time of the non-oscillatory component, but the signature coherent oscillations of the LT phases are not supressed. Above ~5 mJ/cm^2, the relaxation times and amplitudes of the non-oscillatory parts of the response change and produce a distinct anisotropic response not found under low fluence conditions at any of the studied temperatures. Moreover, different effects resulting from exposure to high fluence pulse trains of varying length are revealed in STM. Exposure to short pulse trains results in the healing of defects in the stripe phase. With increasing number of pulses, the periodicity of the stripe order is changed and the LT1 phase is stabilised event at low temperatures, while still longer pulse trains produce a change of orientation of the stripe phase.

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[3] H. S. Kim et. al., Nano Lett. **16**, 7, 4260-4265 (2016)

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