Nonequilibrium Quantum Dynamics and Relaxation Phenomena in Many Body Systems

BOOK OF ABSTRACTS

Ambrož, Krvavec, Slovenia, December 16th – 19th, 2018

Nonequilibrium Quantum Dynamics and Relaxation Phenomena in Many Body Systems

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Nonequilibrium dynamics and relaxation phenomena investigated by HHG time-, spin-, and angle-resolved photoelectron spectroscopy

S. Mathias

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Time- and angle-resolved photoelectron spectroscopy (trARPES) has nowadays emerged as a powerful tool for investigating ultrafast non-equilibrium dynamics at surfaces. In this context, capturing the dynamics of the electronic band structure of a material presents a powerful capability for uncovering the complex couplings between the electronic and structural degrees of freedom [1,2]. When this technique is nowadays combined with a femtosecond high-harmonic generation light source and a novel spin detector, a "complete" photoemission experiment can be realized, with full access to the spin-resolved transient band-structure dynamics on the femtosecond time scale [3]. I will exemplify these capabilities and discuss recent experiments on nonequilibrium dynamics and relaxation phenomena in the transition-metal dichalcogenide $TiSe_2$ [2] and the ferromagnet Cobalt [3].

[1] Rohwer *et al*, Nature 471, 490-493 (2011)
[2] Mathias *et al*., Nature Comm. 7, 12902 (2016)
[3] Eich *et al*., Science Adv. 3, e1602094 (2017)

Ultrafast magnetization dynamics and enhancement of the magnetic state in CoPt alloys

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The recent discovery of all-optical switching in ferromagnetic CoPt has triggered renewed interest in this material and suggested it as a possible candidate for new types of ultrafast and high-density storage media. We have recently found, using a laboratory-based high-harmonic source, that the demagnetization of crystalline CoPt alloys is followed by an enhanced magnetization after several picoseconds. This puzzling behavior could point to the existence of magneto-volume effects. The effect of magnetic enhancement is observed only for the samples with out-of-plane magnetization component and precisely chosen concentration of Pt atoms in the alloy.
Utilizing element-specific time-resolved magneto-optical Kerr spectroscopy, which allows resonant probing of magnetic properties of different subsystems in the material, we show that induced magnetism in Pt reveal distinct dynamics from Co spins. Increasing Pt concentration in the alloy causes faster demagnetization also at Co absorption edges and may be related to improved spin-flip scattering due to large spin-orbit coupling in Pt.

Transient low-frequency cooling by impulse perturbations

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We present a mechanism able to transiently cool down low-energy degrees of freedom through an impulse field whose frequency hits a high-energy exciton-like absorption peak. First we show how such mechanism is realised in an exactly solvable toy-model, consisting of two coupled infinitely-connected quantum Ising models with very different transverse fields. We demonstrate that a properly designed impulse perturbation is able to transiently stabilise a symmetry broken phase, despite the temperature is higher than the critical one and a finite amount of energy is supplied to the system [1].
Next, we speculate that such cooling mechanism might explain the observation of a superconducting-like optical response well above the equilibrium T_c in K_3C_{60} irradiated by a mid-infrared laser pulse [2].

[1] M. Fabrizio, Phys. Rev. Lett. 120, 220601 (2018)
[2] A. Nava *et al*., Nat. Phys. 14, 154 (2018)

Formation of spatial structures by spin-selective excitations

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Strongly Correlated Lattice Gas of Polarons and Charge Density Waves

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Two-dimensional materials display a plethora of different charge ordering phenomena, but the mechanism for the formation of low-temperature commensurate order has proven surprisingly controversial [1,2]. Even though such ordering occurs in many materials, there is often no common point of view on its origin: Fermi surface instabilities associated with nesting [3] or exciton formation [4], the electron-phonon interaction [5] and the Coulomb interaction [6] are commonly discussed, but each case is applied individually, and is applicable in a certain temperature range. The example of 1T-TaS_2 is particularly illuminating, where all the three different mechanisms are proposed for different states at different temperatures [1,6,7].

In this paper we propose an alternative viewpoint of low-temperature states on triangular lattices based on sparse ordering of polarons, subject to (only) screened Coulomb interactions. Using a charged lattice gas model we find stable regularly ordered polaronic crystals at certain *magic filling* fractions f_m that correspond to observed crystal CDW phases for f_m =1/4 (1T-$TiSe_2$, $K_3Cu_8S_6$), 1/9 (2H-TaS_2, 2H-$TaSe_2$, 2H-$NbSe_2$), 1/13 (1T-TaS_2, 4Hb-TaS_2, 1T-$TaSe_2$, 4Hb-$TaSe_2$, 1T-$NbSe_2$) and 1/16 (1T-VSe_2).

For doping near f_m, the model calculation reveals the appearance of a plethora of near-degenerate different domain wall configurations which accommodate the doped charges. At intermediate doping in between different f_m, an apparently infinite number of configurationally near-degenerate states form that lead to an amorphous state, which is stable down to very low temperatures, with a series of possible quantum critical points in the phase diagram. The effective degeneracy of configurational states subject to quantum fluctuations might lead to a quantum *charge* liquid at low temperatures, analoguous to the canonical quantum spin liquid.

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[2] M. Johannes and I. Mazin, Physical Review B 77, 165135 (2008).
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[4] B. Halperin and T. Rice, in *Solid State Physics* (Elsevier, 1968), pp. 115–192.
[5] X. Zhu, Y. Cao, J. Zhang, E. Plummer, and J. Guo, Proceedings of the National Academy of Sciences 112, 2367 (2015).
[6] P. Fazekas and E. Tosatti, Philosophical Magazine B 39, 229 (1979).
[7] F. Clerc, C. Battaglia, M. Bovet, L. Despont, C. Monney, H. Cercellier, M. Garnier, P. Aebi, H. Berger, and L. Forró, Physical Review B 74, 155114 (2006).

Light induced transient dynamics of the charge transfer insulator La_2CuO_4

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We investigate the transient dynamics of La_2CuO_4, the parent compound of the Lanthanum based cuprate high temperature superconductor, upon photo excitation with UV photons across the charge transfer (CT) gap of 2.1 eV. The resulting transient state is studied of extracting the time-evolution of the broadband complex dielectric function in the spectral range of 0.5 – 2.6 eV. Experiments are performed as a function of the excitation density over several orders of magnitude, up to ~ 0.1 absorbed photons/Cu-atom. Modeling the changes in the complex dielectric function with the (induced) Drude – Lorentz model reveals a pronounced renormalization of the CT gap, accompanied by the light-induced mid-gap absorption, resembling the evolution of optical properties by chemical doping. The data provide strong constraints on the possible photogenerated free carrier (Drude) response. We demonstrate, that even at the highest excitation densities, where in the case of comparable chemical doping a metallic state is realized, photodoping results in a negligible density of free carriers, underscoring the underlying Mott physics.

Time-domain identification of electron-boson interaction in high-T_c superconductors

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Non-equilibrium experiments on high-temperature superconductors are believed to reveal fundamental interactions potentially hidden under equilibrium conditions. Using time-resolved photoemission spectroscopy, we identified predominant coupling of photoexcited electrons to particular bosonic excitations in copper- and iron-based superconductors ($BiSr_2CaCu_2O_{8+x}$ and $BaFe_{1-x}Co_xAs_2$, respectively) that are revealed by a pronounced energy dependence of the photoexcited carrier life times [1,2]. In the particular case of BSCCO, the coupling boson was identified as Cu-O-plane phonons using complementary femtosecond electron diffraction experiments [3], while in BaFeAs coupling to magnetic excitations are considered. We belive that these non-equilibrium signatures should also be present in other systems with predominant coupling channels.

[1] J.D. Rameau *et al*. Nature Commun. 7, 13761 (2016)
[2] I. Avigo *et al*. New J. Phys. 18, 093028 (2016)
[3] T. Konstantinova *et al*. Sci. Adv. 4, eaap7427 (2018)

High Field Anomalies of Equilibrium and Ultrafast Magnetism in Rare-Earth Ferrimagnets

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Magneto-optical spectroscopy in fields up to 30 Tesla reveals anomalies in equilibrium and ultrafast magnetism of ferrimagnetic rare-earth-transition metal alloy TbFeCo. In particular, in the vicinity of the magnetization compensation temperature each of the magnetizations of the antiferromagnetically coupled Tb and FeCo sublattices show triple hysteresis loops. Contrary to state-of-the-art theory, which explains it by the sample inhomogeneity, here we show that the loops are an intrinsic property of the rare-earth ferrimagnet. Assuming that the rare-earth ions are paramagnetic and have a non-zero orbital momentum in the ground state and, therefore, a large magnetic anisotropy, we are able to reproduce the experimentally observed behavior in equilibrium. The same theory is also able to predict experimentally observed critical slowdown of ultrafast spin dynamics in the vicinity of the magnetization compensation temperature emphasizing the role played by the orbital momentum in statics and ultrafast magnetism of ferrimagnets.

Towards the nonequilibrium relaxation picture at large timescales

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In the search for the transient emergent states with novel and unexpected functionalities, the understanding of nonequilibrium dynamics is crucial. Quantum statistical mechanics description is available in some cases, but is still quite complex in practical situations [1,2]. Phenomenological approaches of »nonequilibrium thermodynamics« are often used instead. In many cases, the problem is artificially reduced to the scenario with a system finding another local minimum of free energy. However, with the advance of combining STM with femtosecond lasers, we were able to identify the fundamentally different scenarios of non-equilbrium transitions to emergent states, such as melting [3] and jamming [4], or counterintuitive outcomes, such as density wave interference. The revision of the conventional approaches is thus necessary.

With the above technique, we can now observe how the individual realisation of the light-induced state relaxes on nanoscale during the times of 10^0-10^4 seconds. This gives us access to the two-time correlation functions, which can be used to extend the current picture. This talk is an experimentalists' attempt to approach the nonequilibrium relaxation picture of the transient states beyond the simple phenomonlogical arguments.

This work was supported by the ERC Advanced Grant »Trajectory«.

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[4] Ya. A. Gerasimenko, I. Vaskivskyi, J. Ravnik. J. Vodeb, V. V. Kabanov, D. Mihailovic, *arXiv:1803.00255* (2018)

Entanglement dynamics in strongly correlated quantum systems

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Transport engineering in integrable and nonintegrable systems with disorder

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Department of Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia

Spin transport and Drude weight bound in an integrable Floquet driven model

L.Zadnik

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I will discuss quasilocal conservation laws in the Floquet driven XXZ model and their implications on the spin transport. Interestingly, the model exhibits ballistic transport for a range of anisotropies which, in the continuous-time case, belong to the gapped regime.

Solving Chaotic Quantum Many-body System

P. Kos

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When talking about solvable models, we usually have in mind free and integrable models. These models have many special properties, which are different from those of the generic models that are chaotic.

I will demonstrate how using a special property of the duality point of the kicked Ising spin chain, we managed to compute the spectral form factor and the time evolution of the entanglement entropy for a chaotic quantum many-body system. The spectral form factor shows that the model behaves chaotically for any disorder in the magnetic field in the z direction. The dynamics of the entanglement entropy indicates that the information spreads with a maximal speed and saturates to the maximum value.

[1] P. Kos, M. Ljubotina and T. Prosen Phys. Rev. X 8, 021062 (2018)
[2] B. Bertini, P. Kos and T. Prosen, arXiv:1805.00931 (2018)

Are typical Hamiltonian eigenstates similar to random states?

L. Vidmar

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Studies of nonequilibrium dynamics and thermalization of isolated quantum systems have revealed a crucial role played by Hamiltonian eigenstates when establishing a link between quantum dynamics and quantum statistical physics. In my talk, I will shed some new light on the structure of Hamiltonian eigenstates far above the ground state from the perspective of bipartite von Neumann entanglement entropy.

First I will focus on eigenstates of generic many-body Hamiltonians (also denoted as 'quantum chaotic Hamiltonians') with particle number conservation [1]. I will study eigenstates of quantum spin chains in nonintegrable regime, as well as random pure states. The main question I am going to address is how different are typical eigenstates of physical Hamiltonians from typical states in the Hilbert space. In the second part, I will focus on quadratic fermionic Hamiltonians [2], with a particular emphasis on the paradigmatic quantum Ising model in one dimension [3,4]. In this class of Hamiltonians, typical eigenstates are much less entangled than typical states in the Hilbert space. I will argue that the leading term of the average (over all eigenstates) entanglement entropy exhibits a volume-law scaling that is universal for translationally invariant quadratic models. The subleading term is constant at the critical field for the quantum phase transition and vanishes otherwise (in the thermodynamic limit), i.e., the critical field can be identified from subleading corrections to the average entanglement entropy.

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[2] L. Vidmar, L. Hackl, E. Bianchi and M. Rigol, Phys. Rev. Lett. 119, 020601 (2017)
[3] L. Vidmar, L. Hackl, E. Bianchi and M. Rigol, Phys. Rev. Lett. 121, 220602 (2018)
[4] L. Hackl, L. Vidmar, M. Rigol and E. Bianchi, in preparation

Monday, December 17th

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9:25 - 9:50	**R. Steinigeweg**: Impact of eigenstate thermalization on the route to equilibrium	
9:50 - 10:15	**F. Heidrich-Meisner**: Thermalization and eingenstate-thermalization hypothesis in the Holstein polaron model	
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10:35 - 11:00	**P. Werner**: High-harmonic generation in correlated solids	
11:00 - 11:25	**M. Eckstein**:	
11:25 - 11:50	**A. Ramšak**: Stability of non-adiabatic holonomic qubit manipulations	
11:50 - 12:15	**J. Mravlje**: Electronic correlations and spin-orbit coupling in Sr_2RuO_4	
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16:55 - 17:20	**F. Cilento**: Dynamics of correlation-frozen antinodal quasiparticles in superconducting cuprates	
17:20 - 17:45	**J. Kokalj**: Role of charge susceptibility, diffusion and vertex corrections in the study of bad metals with cold atoms	
17:45 - 18:00	**S. Peli**: Mottness at finite doping and charge instabilities in cuprates	
18:00 - 20:00	*Dinner break*	
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20:00 - 20:25	**T. Prosen**: Exact spectral form factor and entanglement dynamics in a minimal model of many-body quantum chaos	
20:25 - 20:50	**M. Kormos**: Spin fluctuations after quantum quenches in the S=1 Heisenberg model: numerical validation of the semiclassical theory	
20:50 - 21:15	**V. Popkov**: Dissipative generation of nonequilibrium quantum steady states with small rank of the quantum sine-Gordon model: experiment and theory	
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Spin, charge and energy transport in strongly disordered Hubbard chains

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We derive and study the effective spin model that explains the anomalous spin dynamics in the one-dimensional Hubbard model with strong potential disorder [1]. Assuming that charges are localized, we show that spins are delocalized and their subdiffusive transport originates from a singular random distribution of spin exchange interactions. The exponent relevant for the subdiffusion is determined by the Anderson localization length and the density of electrons. While the analytical derivations are valid for low particle density, numerical results for the full model reveal a qualitative agreement up to half-filling. The energy transport is shown to be anomalous as well.

[1] M.Kozarzewski, P.Prelovsek, M.Mierzejewski, Phys. Rev. Lett. 120, 246602 (2018)

Impact of eigenstate thermalization on the route to equilibrium

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The eigenstate thermalization hypothesis (ETH) and the theory of linear response (LRT) are celebrated cornerstones of our understanding of the physics of many-body quantum systems out of equilibrium. While the ETH provides a generic mechanism of thermalization for states arbitrarily far from equilibrium, LRT extends the successful concepts of statistical mechanics to situations close to equilibrium. In our work [1], we connect these cornerstones to shed light on the route to equilibrium for a class of properly prepared states. We unveil that, if the off-diagonal part of the ETH applies, then the relaxation process can become independent of whether or not a state is close to equilibrium. Moreover, in this case, the dynamics is generated by a single correlation function, i.e., the relaxation function in the context of LRT. Our analytical arguments are illustrated by numerical results for idealized models of random-matrix type and more realistic models of interacting spins on a lattice. Remarkably, our arguments also apply to integrable quantum systems where the diagonal part of the ETH may break down. If time allows, the special case of fermionic occupation numbers [2] in disordered systems [3] is discussed as well.

[1] J. Richter, J. Gemmer, R. Steinigeweg, arXiv:1805.11625.
[2] J. Richter, R. Steinigeweg, arXiv:1711.00672.
[3] J. Richter, J. Herbrych, R. Steinigeweg, Phys. Rev. B 98, 134302 (2018).

Thermalization and eigenstate thermalization hypothesis in the Holstein polaron model

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High-harmonic generation in correlated solids

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Using nonequilibrium dynamical mean-field theory, we study the high-harmonic generation in wide-gap Mott insulators driven by periodic electric fields. In the strong-field regime, the harmonic intensity exhibits multiple plateaus, whose cutoff energies $\varepsilon_{cut} = U + mE_0$ scale with the Coulomb interaction U and the maximum field strength E_0 [1]. In this regime, the created doublons and holons are localized because of the strong field and the m-th plateau originates from the recombination of m-th nearest-neighbor doublon-holon pairs. While this behavior is analogous to semi-conductors [2], the high-harmonic spectrum of Mott insulators exhibits additional structures associated with multi-particle excitations and, in the multi-orbital case, with Hund excitations. We also consider the high-harmonic generation in spin chains driven by periodic magnetic fields [3].

[1] Y. Murakami, M. Eckstein, and P. Werner, Phys. Rev. Lett. 121, 057405 (2018).
[2] G. Vampa *et al*., Phys. Rev. Lett. 113, 073901 (2014).
[3] S. Takayoshi *et al*., in preparation.

[Title]

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Stability of non-adiabatic holonomic qubit manipulations

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A promising method of qubit malipulation in quantum information processing applications is the manipulation where the Rashba effect in non-adiabatic systems induces quantum phases, including the spin rotation. By the virtue of exact unitary transformations [1] we recently proved that the ratio of the non-adiabatic Anandan phase and the adiabatic Wilczek-Zee counterpart can be tuned to any real number [2].

Stability properties of qubit transformations and the corresponding fidelity can also be studied exactly and as an example we will present results for spin-orbit dynamics influenced by the Ornstein-Uhlenbeck coloured noise of driving fields [3,4]. We will demonstrate also how these non-adiabatic systems can be coupled to thermal baths. In particular, by the known unitary transformation [1] the system can be expressed in the Floquet basis which enables an exact derivation of dissipators and the Lindblad equation. Some typical solutions of the corresponding Lindblad equation will be presented [5].

[1] T. Čadež, J. H. Jefferson, and A. Ramšak, Phys. Rev. Lett. 112, 150402 (2014).
[2] A. Ramšak, T. Čadež, A. Kregar, and L. Ulčakar, Eur. Phys. J. ST 227, 353 (2018).
[3] L. Ulčakar and A. Ramšak, New J. Phys. 19, 093015 (2017)
[4] L. Ulčakar and A. Ramšak, Int. J. Mod. Phys. B 32, 1840028 (2018).
[5] B. Donvil, L. Ulčakar, T. Rejec, and A. Ramšak, in preparation.

Electronic correlations and spin-orbit coupling in Sr_2RuO_4

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Femtosecond covariance spectroscopy

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The success of non-linear optics relies largely on pulse-to-pulse consistency. In contrast, covariance based techniques used in photoionization electron spectroscopy and mass spectrometry have shown that wealth of information can be extracted from noise that is lost when averaging multiple measurements. Here, we apply covariance based detection to nonlinear optical spectroscopy, and show that noise in a femtosecond laser is not necessarily a liability to be mitigated, but can act as a unique and powerful asset. As a proof of principle we apply this approach to the process of stimulated Raman scattering in a-quartz. Our results demonstrate how nonlinear processes in the sample can encode correlations between the spectral components of ultrashort pulses with uncorrelated stochastic fluctuations. This in turn provides richer information compared to the standard non-linear optics techniques that are based on averages over many repetitions with well-behaved laser pulses.

Dynamics of correlation-frozen antinodal quasiparticles in superconducting cuprates

F. Cilento

Elettra Sincrotrone Trieste S.C.p.A., Basovizza I-34149, Italy

Role of charge susceptibility, diffusion and vertex corrections in the study of bad metals with cold atoms

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Mottness at finite doping and charge instabilities in cuprates

S. Peli

Elettra Sincrotrone Trieste S.C.p.A., Basovizza I-34149, Italy

Exact spectral form factor and entanglement dynamics in a minimal model of many-body quantum chaos

T. Prosen

Department of Physics, University of Ljubljana, SI-1000 Ljubljana, Slovenia

Spin fluctuations after quantum quenches in the S = 1 Heisenberg model: numerical validation of the semiclassical theory

M. Kormos

Department of Theoretical Physics, Budapest University of Technology and Economics
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Dissipative generation of nonequilibrium quantum steady states with small rank

V.Popkov,[1,2] C.Presilla[3], J.Schmidt[4]

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We propose a solution to the problem of realizing a predefined and pure quantum state, which is an attractor of the temporal dynamics, based on a simultaneous presence of coherent and dissipative dynamics, in the limit of strong dissipation [1]. This will be generalized to a generic nonequilibrium steady state of a reduced rank.

General criterium is then applied to an open Heisenberg spin chain, dissipatively coupled at the edges to boundary baths with fixed magnetizations. In particular, it will be shown how to create and sustain dissipatively a configuration of fully polarized spins arranged in a helix along the chain. Such a spin-helix is a pure quantum state with nontrivial topology, characterized by ballistic magnetization current.

[1] V.Popkov, C. Presilla and J. Schmidt, Phys. Rev. A 95 052131 (2017)

Spectral form factor and many-body localization

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The statistical properties of the energy spectra of ergodic and many-body localized systems are significantly different. In this talk I discuss how the calculation of the spectral form factor (SFF) allows for discrimination between ergodic and many-body localized (MBL) systems. In the former case, the calculated values of SFF should match the ones observed in the so-called gaussian orthogonal ensemble (GOE) of random matrices, where a universal regime of linear growth is observed in the parameter region between the Thouless and the Heisenberg time. The results are completely different in the MBL phase, where they match those for systems in which the energy levels are distributed independently according to the Poisson probability distribution. Consequently, linear growth of the SFF is not observed in MBL sytems. As opposed to more standard statistical approaches towards the investigation of the MBL transition, such as the calculation of the mean ratio of the adjacent level-spacings, the calculation of SFF accounts for correlations between all the energy levels in the spectrum. It thus allows for a more comprehensive insight in the system's properties, such as its behaviour at different time scales, at the expense of a more involved numerical implementation.

Tuesday, December 18th

	Chair: D. Fausti	
9:00 - 9:25	**C. Giannetti**: Controlling the birth and growth of metallic nanodroplets across the martensitic Mott transition of V_2O_3	
9:25 - 9:50	**D. Arčon**: A new high-temperature quantum spin liquid with polaron spins	
9:50 - 10:15	**P. Prelovšek**: Searching for a spinon in the triangular Heisenberg model	
10:15 - 10:35	*Coffee break*	
	Chair: C. Giannetti	
10:35 - 11:00	**D. Mihailović**: Quantum metastability in non-equilibrium toy systems	
11:00 - 11:25	**J. Zhao**: Ultrafast quasiparticle dynamics and electron-phonon coupling in monolayer FeSe/$SrTiO_3$ and bulk $(Li_{0.84}Fe_{0.16})OHFe_{0.98}Se$	
11:25 - 11:50	**C. Monney**: Ultrafast dynamics of short-range magnetic correlations in a spin-chain cuprate	
11:50 - 12:05	**D. Kopić**: Fingerprint of the photoinduced nematic state in $FeSe_{0.4}Te_{0.6}$ revealed by TR-ARPES	
12:05 - 16:30	*Lunch break*	
	Chair: P. Werner	
16:30 - 16:55	**D. Iyer**: Quench dynamics of localized zero-modes in graphene	
16:55 - 17:20	**D. Luitz**: Anomalous thermalization close to MBL phases	
17:20 - 17:45	**P. Karpov**: Phase transitions and pattern formation in ensembles of phase-amplitude solitons in quasi-1D electronic systems	
17:45 - 18:10	**V. Kabanov**: Quantum oscillations and Zeeman splitting in doped antiferromagnetic insulators	
18:10 - 20:00	*Dinner break*	
	Chair: F. Cilento	
20:00 - 20:15	**F. V. Nasretdinova**: The phase diagram of the unusual CDW oxide Mo_8O_{23} in equilibrium and under transient photodoping	
20:15 - 20:30	**M. Naseska**: Ultrafast spin density wave dynamics in iron-based pnictides at intense optical pulse excitations	
20:30 - 20:45	**A. Ronchi**: Nanoscale dynamics of the Mott transition in the correlated insulator V_2O_3	
20:45 - 21:00	**G. Lemut**: Transport properties of a Weyl superconductor with a vortex lattice	
21:00 - 23:00	*Social event*	

Controlling the birth and growth of metallic nanodroplets across the martensitic Mott transition of V_2O_3

C. Giannetti

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Quantum spin liquid in 1T-TaS_2

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The Anderson's proposal of a resonating valence bond state [1] was put forward to account for the unusual magnetic properties of a triangular atomic lattice of Ta atoms in the layered transition metal dichalcogenide 1T-TaS_2. Compared to some recent candidates for quantum spin liquids (QSL) on triangular lattice, e.g., $YbMgGaO_4$ [2] or κ-$(ET)_2Cu_2(CN)_3$ [3], layered dichalcogenides have perfect triangular lattice geometry and a weaker spin-orbit coupling, offering a possibility for obtaining a unique insight into the competition between antagonistic QSL and Néel states. Here we report [4] on a QSL that appears to be realized by atomic-cluster spins on the triangular lattice of a charge-density wave (CDW) state of 1T-TaS_2. In this system, nuclear magnetic quadrupole resonance and muon spin relaxation experiments reveal that the spins show gapless quantum spin liquid dynamics and no long range magnetic order down to 70 mK. Canonical T^2 power-law temperature dependence of the spin relaxation dynamics characteristic of a QSL is observed from 200 K to T_f = 55 K. Below this temperature we observe a new gapless state with reduced density of spin excitations and high degree of local disorder signifying new quantum spin order emerging from the QSL. Interestingly, at the lowest temperatures the spin-lattice relaxation changes to sublinear dependence following $\sim T^{0.6}$ power law dependence, which is characteristic of QSL with spinon Fermi surface. The QSL is at first robust against applying chemical pressure in doped samples before giving a way to superconducting state.

[1] P. W. Anderson, Materials Research Bulletin 8, 153 (1973).
[2] Y. Shen, et al., Nature 540, 559 (2016).
[3] T. Itou, A. Oyamada, and R. Kato, Nature Physics 6, 673 (2010).
[4] M. Klanjšek, A. Zorko, R. Zitko, J. Mravlje, Z. Jagličić, P. K. Biswas, P. Prelovšek, D. Mihailovic, and D. Arčon, Nature Physics 13, 1130 (2017).

The search for a spinon in frustrated Heisenberg models

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In the talk I will discuss the status of the understanding of possible spin-liquid phase within the S=1/2 Heisenberg models on triangular lattices and open questions in relation to experiments on materials being the realization of such models. Further I will present a new approach based on the reduced basis for basic triangular plaquettes which allows the unifying treatment of generalized Heisenberg models on triangular and kagome lattices, being supported also by existence of smagnetization plateaus in external field. It will be shown that such a formulation reveals the stability of ordered antiferromagnetism on a triangular lattice with only neighbor exchange, but also its instability when next neighbour coupling is introduced. A simple mean-field approximation in the latter phase indicates on a spin liquid with a spinon Fermi surface.

Quantum metastability in non-equilibrium toy systems

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Ultrafast quasiparticle dynamics and electron-phonon coupling in single-layer FeSe/$SrTiO_3$ and $(Li_{0.84}Fe_{0.16})OHFe_{0.98}Se$

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Distinctive superconducting behaviors between bulk and monolayer FeSe make it challenging to obtain a unified picture of all FeSe-based superconductors. Here, we investigate the ultrafast quasiparticle dynamics of an intercalated superconductor $(Li_{1-x}Fe_x)OHFe_{1-y}Se$, which is a bulk crystal but shares a similar electronic structure with single-layer FeSe on $SrTiO_3$. We obtain the electron-phonon coupling (EPC) constant λ (0.24 ± 0.03), which well bridges that of bulk FeSe crystal and single-layer FeSe/$SrTiO_3$ [1]. Moreover, we find that such a positive correlation between λ and superconducting T_c holds among all known FeSe-based superconductors, even in line with reported FeAs-based superconductors. Our observation indicates possible universal role of EPC in the superconductivity of all known categories of iron-based superconductors, which is a critical step towards achieving a unified superconducting mechanism for all iron-based superconductors.

[1] Y. C. Tian, Jimin Zhao *et al.*, Ultrafast dynamics evidence of high temperature superconductivity in single unit cell FeSe on $SrTiO_3$. Phys. Rev. Lett. 116, 107001 (2016).

Ultrafast dynamics of short-range magnetic correlations in a spin-chain cuprate

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Resonant inelastic x-ray scattering (RIXS) is a powerful x-ray spectroscopy that is sensitive to all degrees of freedom of condensed matter. With the development of x-ray free electron lasers (XFEL), it becomes now possible to perform time-resolved RIXS to access their time-domain dynamics.

Here I will first present static RIXS data obtained at O *K*-edge on the quasi-one-dimensional spin-chains $CuGeO_3$ at the ADRESS beamline at Swiss Light Source. In this edge-sharing chain cuprate having a standard Cu d9 electronic configuration, RIXS can create a particular excitation called a Zhang-Rice singlet (ZRS) in its final state. The ZRS consists in a double-hole occupation on a CuO_4 plaquette, which occurs via an effective hole transfer from one plaquette to another. The intensity of this excitation depends on the ground state spin configuration and is a measure of the nearest-neighbour spin arrangement. This effect is used here to monitor the intrachain short-range spin correlations in $CuGeO_3$ as a function of temperature [1].

I will also present recent time-resolved RIXS data obtained at the SXR beamline of the XFEL LCLS. After photoexciting $CuGeO_3$ with 266 nm photon pulses, we observe a transient suppression of the ZRS intensity within a few picoseconds. Its recovery is then tracked over hundreds of picoseconds. This allows us to monitor the ultrafast dynamics of short-range spin correlations $CuGeO_3$.

[1] C. Monney *et al.*, PRL 110, 087403 (2013)

Fingerprint of the photoinduced nematic state on $FeSe_{0.4}Te_{0.6}$ compuond revealed by TR-ARPES

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The $FeSe_xTe_{1-x}$ system, despite being the structurally simple among iron-based superconducotrs, displays several puzzling properties, ranging from nematicity on the Se-rich side of its phase diagram to magnetism on the opposite Te-rich side [1,2]. In this frame, the role of electronic correlation in this material is strongly debated. Here we study the electron dynamics of the $FeSe_{0.4}Te_{0.6}$ compound by polarization-dependent time- and angle- resolved photoelectron spectroscopy. Thanks to orbital selectivity, we reveal a nonequilibrium metastable state that is compatible with a photoinduced nematic phase, not present under equilibrium conditions. We argue that the photoinduced nematic phase, triggered by a high-energy ultrafast excitation perturbing the C_4 symmetry, is determined by electronic correlations induced by Hund's coupling. This finding indicates the importance of electronic correlations for the physics of the $FeSe_xTe_{1-x}$ system, and established the importance of an ultrafast excitation as a handle to trigger nematic phases in matter.

[1] G. R. Stewart, Rev. Mod. Phys. 83, 1589 (2011)
[2] M. Yi, Y. Zhang, Z.-X. Shen, and D. Lu, Quantum Materials 2, 57 (2017)

Quench dynamics of localized zero-modes in graphene

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Anomalous thermalization close to MBL phases

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While generic interacting isolated quantum systems typically satisfy the eigenstate thermalization hypothesis (ETH) and thermalize, this is not the case for many-body localized systems. Using two examples, a static and a periodically driven one, I will show that there are corrections to ETH also in the thermal phase at weak disorder of disordered interacting spin chains, which are related to slow subdiffusive spin transport. They lead to a different scaling of matrix elements of the local S_z operator with system size compared to the standard ETH and are accompanied by non-Gaussian distributions of these matrix elements.

[1] S. Roy, Y. Bar Lev, and D. J. Luitz, Phys. Rev. B 98, 060201(R)
[2] D. J. Luitz and Y. Bar Lev, Phys. Rev. Lett. 117, 170404

Phase transitions and pattern formation in ensembles of phase-amplitude solitons in quasi-one-dimensional electronic systems

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Most common types of symmetry breaking in quasi-one-dimensional electronic systems possess a combined manifold of states degenerate with respect to both the phase θ and the amplitude A of the order parameter A*exp($i\theta$). These degrees of freedom can be controlled or accessed independently via either the spin polarization or the charge densities. To understand statistical properties and the phase diagram in the course of cooling under the controlled parameters, I will present an analytical treatment supported by Monte Carlo simulations for a generic coarse-grained two-field model of XY-Ising type. The degeneracies give rise to two coexisting types of topologically nontrivial configurations: phase vortices and amplitude kinks − the solitons. In 2D, 3D states with long-range (or BKT type) orders, the topological confinement sets in at a temperature $T=T_1$ which binds together the kinks and unusual half-integer vortices. At a lower $T=T_2$, the solitons start to aggregate into walls formed as rods of amplitude kinks which are ultimately terminated by half-integer vortices. With lowering T, the walls multiply pass sequentially across the sample. Overcooling the system after the initial pumping promotes the growth of such solitonic walls.

These results indicate a possible physical realization of a peculiar system of half-integer vortices with rods of amplitude kinks connecting their cores. Its experimental realization becomes feasible in view of recent successes in real space observations and even manipulations of domain walls in correlated electronic systems.

Zeeman splitting in doped antiferromagnetic insulators

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The Zeeman splitting of the conduction electrons in dopped antiferromagnetic insulators is considered. In the case of weak spin-orbit interaction the splitting is absent for the electrons in the magnetic Brillouin zone boundary and direction of the external field perpendicular to the lattice magnetization. In the case of strong spin-orbit coupling the splitting is absent only in isolated points of the Brillouin zone boundary for some selected directions of the field. The dependence of the g-factors on magnetic field is discussed.

The phase diagram of the unusual CDW oxide Mo_8O_{23} in equilibrium and under transient photodoping

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Molybdenum oxides are stable in many crystal structures that differ only slightly in Mo:O ratio yet demonstrate fascinating phase diagrams with correlated and sometimes competing orders, including charge density waves (CDW) and, if doped with alkali atoms, superconductivity [1-2]. With recent studies demonstrating how precise vacancy doping control reveals new perspective charge storage properties of well-studied parent oxide MoO_3 [3] and how the transient photodoping of some other TMOs induces phases not found in equilibrium [4,5] it is interesting to try and tune less well-studied molybdenum oxides' phase diagrams by the least invasive doping method available – transient photodoping. Mo_8O_{23} is an excellent example of a system with a predisposition to be transiently photodoped – it is an anisotropic semimetal with a very asymmetric density of states at high temperatures. Here we report studies of equilibrium and photodoping-tuned phase diagrams of the Mo_8O_{23} by means of various transport, spectroscopy and microscopy probes, supported by DFT calculations. We find that in equilibrium the electron structure is strongly temperpature-dependent and the incommensurate CDW order developed below T_{ICDW} = 343 K gaps just part of the Fermi surface, while another gap develops below 60 K involving the rest of the carriers and signatures of FS reconstruction are observed at intermediate temperatures around 150 K. We report the existence of charge order induced by single 50-femtosecond pulse in the fully gapped state that is stable up to ~350 K but lacks an incommensurate phase. We discuss the possible mechanisms driving the equilibrium and photoinduced phase transitions in Mo_8O_{23}.

This work was supported by ERC Advanced Grant »Trajectory«

[1] *Low-Dimensional Electronic Properties of Molybdenum bronzes and oxides* ed. C. Schlenker, Kluwer Academic Press, Dordrecht (1989)
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[3] H.-S. Kim et al. Nat. Mater. 16, 454–460 (2017)
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[5] V. R. Morrison *et al,* Science 346, 445–448 (2014).

Ultrafast spin density wave dynamics in iron-based pnictides at intense optical pulse excitations

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Ultrafast time-resolved spectroscopy has become an important tool for studying rapidly evolving phase transitions [1-4] because it offers an insight into microscopic process happening during the transition, which cannot be observed in equilibrium experiments. Here we present the ultrafast all-optical time-resolved spectroscopy measurements of the system trajectory through a spin density wave (SDW) phase transition in $SrFe_2As_2$ and $EuFe_2As_2$. Using the standard pump-probe technique we estimated the threshold fluence for a nonthermal destruction of the SDW order ($F_{th} \approx 0.3$ mJ/cm^2) at two different pump-photon energies (1.55 eV and 3.1 eV). Using the multi-pulse pump-probe technique the SDW order destruction timescale of ~150 fs was found to be fluence independent. By comparing the temperature dependences of the standard and multi-pulse transient reflectivity long after the arrival of the destruction pulse we determined the transient lattice heating in $SrFe_2As_2$. At high excitation densities (~mJ/cm^2) the destruction pulse penetration depth significantly exceeds the equilibrium penetration depth suggesting absorption saturation. Using the multipulse pump-probe technique we also measured the recovery of the SDW order at different destruction fluences. The fluence of the destruction pulse was used as an adjustable parameter to control the quench conditions [5]. In the case of the fast quench ($F <$ ~1 mJ/cm^2), when the final lattice temperature does not exceed the SDW transition temperature, the ordered state recovers on a sub picosecond timescale. The SDW state recovery can be sufficiently well described within the framework of a three temperature model (3TM). The 3TM simulation results suggest that: (i) the SDW destruction timescale is set by the thermalization of the initially excited electronic distribution; (ii) the recovery rate depends on the destruction pulse fluence and is governed by cooling of the optical phonons to the lattice bath. The fluence dependent recovery timescale can be attributed to the opening of an electronic relaxation channels upon suppression of the pseudogap related to nematic fluctuations in addition to the anharmonic-decay channels.

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Dynamics of antiferromagnetic martensitic-like nano-domains across the insulator-to-metal transition in V_2O_3

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[6]*Dipartimento di Fisica, Università degli Studi di Trieste, 34127 Trieste, Italy*
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Mott insulators are a class of quantum materials highlighting the most promising properties and functionalities for the next generation of solid-state devices. In the variety of the Mott systems, vanadium-based oxides have been intensively studied due to the possibility of controlling the Mott transition in several suitable ways by changing the chemical doping, temperature, pressure, and, more recently, by applying external electric fields or by ultrafast laser excitations [1]. In particular, we will focus on vanadium sesquioxide (V_2O_3), a prototypical Mott insulator that exhibits a Insulator-to-Metal transition (IMT) occurring at T_{MIT} ~160 K and characterized by a resistivity change of several orders of magnitude. Despite this, the microscopic mechanism driving the IMT in this material is still the subject of a lively debate and recent results unveiled a complex interplay between electronic correlations, lattice deformation and intrinsic inhomogeneities at the nanoscale [2]. Here, we present a study, based on photoemission electron microscopy (PEEM), of the temperature-driven IMT in V_2O_3 films, epitaxially grown on Al_2O_3 [3]. In particular, by tuning the photon energy across the vanadium $L_{2,3}$-edge (≈513 eV), we imaged the formation of antiferromagnetic insulating martensitic-like [4] nano-domains oriented along the V_2O_3 crystallographic directions. Therefore, we investigated both their melting during the thermally-driven IMT and their spatial morphology. These results shed new light on the microscopic mechanisms underlying the IMT and paves the way to better understanding the best approach for controling Mott systems in future applications.

[1] C. Giannetti *et al* 2016, *Adv. Phys.* 65, 58
[2] A.McLeod *et al*. 2017. *Nat. Phys.* 13, 80
[3] P. Homm *et al*. 2015, *App. Phys. Lett.* 107, 111904
[4] A. Roitburd and G. Kurdjumov, Materials Science and Engineering 39, 141 (1979)

Transport properties of a Weyl superconductor with a vortex lattice

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It has long been thought that superconductors cannot support Landau levels since they are destroyed by the appearance of Abrikosov vortices. Recently it was shown that this restriction does not hold for a Weyl superconductor where the vortices do not spoil the topologically protected zeroth Landau level [1]. The low energy dynamics of the Weyl superconductor in a vortex lattice are governed by chiral modes with mixed charge. If we introduce a constant vector potential we can shift the Weyl cones in the Brillouin zone and couple them, which gives rise to chargeless Majorana modes bound to the vortex cores. To observe this transition we have studied the transport properties of such a system when connected to leads. We were able to obtain agreeing analytic and numerical results of these transport signatures.

[1] M.J.Pacholski *et al*, Phys. Rev. Lett. 121, 037701(2018)

Wednesday, December 19th

	Chair: J. Zhao	
9:00 - 9:25	**L. Rettig**: Strongly correlated materials investigated by complementary time-domain techniques	
9:25 - 9:50	**S. Gerber**: X-ray free-electron lasers - a new probe for quantum matter	
9:50 - 10:05	**P. Franceschini**: Fano resonances in halide perovskite nanoparticles	
10:05 - 10:35	*Coffee break*	
	Chair: T. Mertelj	
10:35 - 10:50	**J. Ravnik:** Induced topological charge order in interfering polytype superlattices	
10:50 - 11:05	**J. Skolimowski**: DC-transport properties of correlated electrons in presence of binary disorder	
11:05 - 11:20	**A. Mraz**: Ultrafast low energy memory devices based on TaS_2	
11:20 - 11:35	**D. Michele**: STM visualization of classical and quantum relaxation processes in a metastable state	
11:35 - 11:50	*Closing*	

Strongly correlated materials investigated by complementary time-domain techniques

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X-ray free-electron lasers – a new probe for quantum matter

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Time- and energy-resolved study of Fano Resonances in Halide Perovskite Nanoparticles

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In the last decades, lead halide perovskites have attracted great scientific interest due to their outstanding properties, such as high absorption coefficients, tunable band-gaps and emission wavelengths, long carrier diffusion lengths, and room temperature exciton [1,2,3]. These features, combined with low-cost fabrication methods, determined their key role in the development of high-efficiency photovoltaic solar cells (with power conversion efficiency exceeding 20% [4,5]) and optoelectronic devices [6]. Recently, halide perovskite nanoparticles have been also proposed as white-light emitting metadevices since they exhibit hybrid tunable Fano resonances that originate from the coupling of the excitons to the geometry-induced Mie modes [3]. Here we will present time- and energy-resolved pump-probe measurements showing how the tunable Fano resonance strongly influences the out-of-equilibrium dynamics of these systems.

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Induced topological charge order in interfering polytype superlattices

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Stacking the layers of two-dimensional systems has recently been shown to lead to superconductivity in magic-angle graphene superlattices [1], suggesting that systems with exotic emergent properties may be created by stacking different superlattices.

Here, we report on a low-temperature laser-induced polytype transformation, where we create a single trigonal H-TaS_2 layer on the surface of an orthorhombic 1T-TaS_2 single crystal. Following the transformation, we observe a remarkable new double-stripe modulation of the density of states (DOS) with the period of ~18 nm. The stripes are not aligned either with the atomic lattice or with the CDW direction in either the 1T or H phase. They are found to be perfectly uniform over 1 μm^2, without a single defect. Apart from stripes, we observe a weak CDW modulation from the 1T-TaS_2 crystal below. The stripes remain stable and unchanged if no external stimuli are present.

Upon heating above 77K, the uniform double-stripe state starts to become intertwined. Thus, at ~120 K, we observe the appearance of six-fold knots, formed by intersecting neighboring stripes. The knots first start appearing quasi randomly on the sample, often next to defects. With increasing the temperature, more and more knots start appearing next to each other, forming straight lines and connecting the neighboring stripes. The knots become more and more frequent, and at 220 K we can already observe regions, where knots cover the entire surface, forming an irregular hexagonal lattice.

Our case of a transformed monolayer gives us an interesting combination of a material near the 2D limit, combined with interlayer strain, which leads to new interesting states. Specifically, in the 1H state, thinning the material to the limit is already catching attention, since it has been shown that the critical superconducting temperature rises when the material is thinner [2], as opposed to other materials [3], where it usually drops.

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Dc-transport properties of correlated electrons in presence of binary disorder

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The Hubbard model with binary disorder is known to undergo a metal-insulator transition (MIT) away from half-filling at T=0 for strong enough disorder. To analyse the consequences of this phenomenon on transport a combination of the coherent potential approximation and the dynamical mean-field theory was employed. The results on the temperature dependence of longitudinal resistivity (LR) and cotangent of Hall angle (COHA) show two distinct behaviours depending on the electron filling (n). When n coincides with the disorder concentration (x) LR and COHA become non-monotonic functions of T upon increasing the disorder strength. Signalling the appearance of Mott physics. These behaviour is absent for n different then x, where LR and COHA display a typical for hole doped Mott insulators T-dependence. The results for thermopower revel a universal temperature dependence for x>n>1, with two zero crossings. The obtained results also shed some light on the fate of the MIT at non-integer filling for T>0.

Ultrafast low energy memory devices based on TaS_2

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We have been in search of new technologies that would allow for the development in computer science for quite some time. One of them main building blocks is the computer memory, which has seen a lot of progress in the recent years mainly due to the new memory technologies. 1T-TaS_2 exhibits many different phase states such as charge density wave (CDW), superconductivity [2], Mott insulator transition and the metallic hidden (H) state. Memory devices based on 1T-TaS_2 have been shown to be a good candidate in future supercomputing applications, since they operate at very low temperatures, have low writing energy, are non-volatile [1] and are possible to integrate into large scale systems. It can be used as a memory element that works by switching between different discrete electronic states, which is seen as a change in its electrical resistivity. The switching is done with simple electronic pulses and that makes it very attractive and easy to use.
Here we report on the scaling properties of the 1T-TaS_2 memory devices both in size as in switching power per bit P_b, where $P_b = E_b/\tau$ given in terms of the energy per bit E_b and pulse length τ. The lowest P_b achieved with a basic device in pulsed mode using 60 nm feature size fabricated at PSI with a switching voltage of ~ 0.5 V is $P_b \simeq 1\times10^{-4}W$. With pulse widths of 5 ns and 40 ps typical for electronic and MSM triggered drive pulses, this gives values of $E_b \simeq 500fJ/bit$ and $\sim 5fJ$ respectively. For comparison, the record reported to date is $E_b \simeq\ 40\ fJ/bit$ [3] for a magnetic anisotropy memory. By combining a short pulse superposed onto a DC signal, we were able to lower the switching voltage even further to 0.3 V. Furthermore, intermediate resistive states have been shown to be quite stable, which could lead to even further reduction of switching energy.

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STM visualization of classical and quantum relaxation processes in a metastable state

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Tantalum disulfide (TaS2) is well known for its rich phase-diagram due to the copresence of different types of interaction. This includes three charge density waves states: incommensurate, nearly-commensurate and commensurate (Mott insulator). Moreover, the crystal manifests an additional perturbation-induced metastable state different from any other at the equilibrium. We studied the relaxation process of this metastable state under STM. The STM nanoscale resolution permitted to detect individual polarons in the crystal's surface. This gave us the opportunity to extract the rate of polaons' movements by following the dynamics of the relaxation process. At high temperature (T>20 K) the rate is temperature dependent and it can be explained by a classical hopping model. However, at lower temperatures we found a temperature independent regime, which we interpreted as the evidence of quantum tunnelling phenomena.

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