Workshop on „Short-time Dynamics in Strongly Correlated Systems and Novel Superconductors”, Bochum, Germany, February 18-21, 2013

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TIMETABLE AND BOOK OF ABSTRACTS

Mercator Research Center Ruhr
Eine Initiative der Stiftung Mercator und der Universitätsallianz Metropole Ruhr

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LOCATION AND DATES

The workshop will be held from February 18 – 21, 2013 in the campus of Ruhr University Bochum, Germany.

REGISTRATION

The registration desk will be open on Monday, February 18th , from 08:00 to 10:00. From Tuesday 19th to Thursday 21th the desk will be open from 8:00 to 9:00 in the morning.

TRAVEL INFORMATION

Bochum is well connected by rail to all major cities in Germany. Rail tickets can be booked via Deutsche Bahn. The nearest airport is Düsseldorf International Airport. To reach Bochum from there take first the skyline to the Railway station of the Düsseldorf Airport. From the station take any train (either S-Bahn,

regional RE, or intercity IC/ICE) which stops at the Bochum main station (Bochum Hauptbahnof). Note that at the weekend the trains operate in 20 minutes interval.

VENUE

The workshop takes place at the campus of the Ruhr-University Bochum, Germany. To reach the campus from the Bochum main station (Bochum Hauptbahnof), either take a taxi from the Hauptbahnof (fare is typically 10 euros) or take the U35 line in the direction of Querenburg Hustadt and alight at the Ruhr Universität station. Turn right from the exit. Keep walking till you pass the University Bibliothek on your right, and continue until you reach the University "Mensa" Building. Once in the "Mensa" Building take the elevator to the level 04 Veranstaltungszentrum. The workshop will be in the Hörsaal 3.

Map of the Ruhr-Universität Campus

CONTACT INFORMATION

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For any questions please do not hesitate to contact us by email at:

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SCIENTIFIC PROGRAM

Invited speakers will be allotted 40 minutes including questions. Contributed talks will be for 25 minutes including questions. Projector for computer presentations will be provided.

Poster session will be held on Tuesday.

SOCIAL PROGRAM

Excursion

An excursion to the Deutsches Bergbau Museum will be arranged on Wednesday afternoon. The excursion will start at 15:00 and the participants are expected to meet at the entrance Hall of the Museum. The museum can be easily reached from the University Campus by U35 metro line (U-Bahn Station "Deutsche Bergbau Museum"), the trip takes approximately 20 mins. The link of the museum is given below

http://www.bergbaumuseum.de/index.php?page=1

Social Dinner

The social dinner of the workshop will take place on Wednesday evening at 18:30 hours in the Restaurant Altes Brauhaus Rietkötter. It is only 5 minutes from the Deutsche Bergbaumuseum by foot.

http://www.altes-brauhaus-rietkoetter.de/

Time Table

Monday February 18. 2013

08:45-09:00 **Arrival & Opening**

Chairperson: U. Bovensiepen

09:00-09:40 **Martin Wolf,** *"Transient electronic structure and lattice dynamics of photoexcited solids."*

09:40-10:20 **Pedro M. Echenique,** *"Electron dynamics at surfaces and nano structures."*

10:20-11:00 **Coffee break**

Chairperson: I. Eremin

11:00-11:40 **Michael Bauer,** *"The puzzling CDW-phase of 1T- TiSe2 from a TR-ARPES point of view."*

11:40-12:05 **Volker Meden,** *"Luttinger liquid universality in the time evolution after an interaction quench."*

12:05-12:30 **Marco Schiro,** *"Dynamics of correlated electrons and phonons after sudden excitations."*

12:30-14:00 **Lunch**

Chairperson: D. Hägele

14:00-14:40 **Manfred Fiebig,** *"Optical magnetization control in EuO films."*

14:40-15:05 **Wolfgang Hübner,** *"Ab initio theory for ultrafast dynamics in two- and three- magnetic-center molecules."*

15:05-15:30 **Ilie Radu,** *"Exploring ultrafast magnetism with X-rays and THz radiation."*

15:30-16:10 **Coffee break**

Chairperson: G. Uhrig

16:10-16:35 **Frithjof Anders,** *"A hybrid time-dependent numerica renormalization group approach for strongly correlated quantum impurity systems."*

16:35-17:00 **Dirk Schuricht,** *"Quench dynamics in one-dimensional massive field theories: Ising field theory and sine-Gordon model."*

17:00-17:40 **Corinna Kollath,** *"Correlation dynamics in ultracold atomic gases."*

17:40-18:20 **Stefan Kehrein,** *"Spatiotemporal buildup of correlations in the Kondo model."*

18:30-19:30 **Dinner**

19:30-19:45 **Dagmar Eberle,** *"Mercator Research Center Ruhr: short introduction."*

19:45-20:30 **Jörg Fink,** *"ARPES and tr-ARPES, two complementary techniques for the investigation of unconventional superconductors."*

Tuesday February 19, 2013

Chairperson: C. Kollath

09:00-09:40 **Jim Freericks, "***Theory for pump/probe experiments in charge-density-wave systems."*

09:40-10:20 **Dirk Manske,** *"Density-matrix theory for time-resolved dynamics of superconductors in non-equilibrium."*

10:20-11:00 Coffee break

Chairperson: M. Betz

11:00-11:40 **Thomas Devereaux,** *"Theory for time-domain photon spectroscopy."*

11:40-12:05 **Thomas Fauster,** *"Dynamics of topological surface states on topological insulators investigated by time-resolved two-photon photoemission."*

12:05-12:30 **Matthias Hengsberger,** *"Coherent phonons in one-dimensional atomic chains: Bi(114)."*

12:30-14:00 Lunch

Chairperson: D. Suter

14:00-14:25 **Peter Prelovsek,** *"Charge recombination in photoexcited Mott-Hubbard insulator."*

14:25-14:50 **Ralf Schützhold,** *"Equilibration versus Thermalisation in the Bose & Fermi Hubbard model."*

14:50-15:30 **Andrea Cavalleri,** *"Optical control in quantum solids."*

15:30-16:10 Coffee break

16:10-19:00 Poster session

Wednesday February 20, 2013

Chairperson: H. Zabel

09:00-09:40 **Thomas Elsässer,** *"Correlated electron and lattice dynamics in ionic materials spatially resolved by ultrafast x-ray diffraction."*

09:40-10:20 **Alexander Lichtenstein,** *"Dual-fermion approach to non-equilibrium strongly correlated problems."*

10:20-11:00 Coffee break

Chairperson: H. Kroha

11:00-11:25 **Johan Mentink,** *"Dynamics of correlated spins on the timescale of the exchange interaction."*

11:25-12:05 **Andreas Alvermann,** *"Numerical schemes for time-propagation of strongly correlated systems."*

12:05-12:45 **Martin Eckstein,** *"Nonthermal symmetry-broken states in the Hubbard model."*

12:45- Lunch

14:20-15:00 Travel to excursion

15:00- Deutsches Bergbau museum guided tour

18:30-22:00 Conference dinner

Thursday February 21, 2013

Chairperson: A. Lanzara

09:00-09:40 **Dragan Mihailovic,** *"Coherent trajectories through phase transitions in layered chalcogenides and related systems."*

09:40-10:20 **Hans Kroha,** *"Theory for tuning the ultrafast magnetic dynamics in Gd-Doped EuO."*

10:20-11:00 Coffee break

Chairperson: A. Wieck

11:00-11:40 **Marcus Kollar,** *"Prethermalization and thermalization of weakly interaction quantum systems."*

11:40-12:05 **Mikhail Croitoru,** *"Coherent dynamics of pairing in a superconducting nanowire."*

12:05-12:30 **Jamal Berakdar,** *"Attosecond dynamics of light absorption and refraction in fullerenes."*

12:30-14:00 Lunch

Chairperson: K. Morgenstern

14:00-14:40 **Jure Demsar,** *"Femtosecond photodoping phenomena in cuprate high-T_c Superconductors."*

14:40-15:20 **Claudio Gianetti,** *"In search for the pairing glue in cuprates by non-equilibrium optical spectroscopy."*

15:20-16:00 Coffee break

Chairperson: D. Mihailovic

16:00-16:40 **Alessandra Lanzara,** *"Probing the non-equilibrium momentum dependent dynamic of high temperature superconductors by time-resolved photoemission spectroscopy."*

16:40-17:20 **Alfred Leitenstorfer,** *"Elementary dynamics of quantum correlations in solids studied via ultrabroadband terahertz technology."*

17:20-17:30 Closure

Book of Abstracts

Transient electronic structure and lattice dynamics of photoexcited solids

Martin Wolf

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The electronic properties of solids are often governed by many-body correlation effects and strong electron-phonon coupling leading to phenomena like superconductivity, metal-insulator transitions and the formation of various broken symmetry ground states. One example for the coupling between electronic and phonon degrees of freedom are phase transitions in charge-density wave (CDW) materials where at low temperature a periodic lattice distortion leads to an opening of an electronic gap at the Fermi surface. Ultrafast optical excitation can induce non-equilibrium phase transitions as well as electronic and geometrical structure changes in such complex materials on femtosecond timescales, which can be probed in detail by various time-resolved spectroscopic techniques.

In this talk I will discuss several examples of photoinduced insulator-to-metal transitions studied by time resolved photoelectron and optical spectroscopy [1]. In these systems (TaS_2, $TbTe_3$, VO_2) the insulating ground state is mediated by different mechanisms and ultrafast optical excitation triggers pronounced transient changes of the electronic structure coupled to coherent lattice excitations. These studies demonstrate the need for deeper theoretical understanding.

[1] *Dynamics at Solid State Surfaces and Interfaces, Vol. 1: Current Developments*, Eds.: U. Bovensiepen, H. Petek, M. Wolf; Wiley-VCH, Weinheim, Germany, (2010)

Electron dynamics at surfaces and nanostructures

P.M. Echenique

Dpto. de Física de Materiales UPV-EHU, Donostia International Physics Center (DIPC) and Material Physics Center (CFM), P. Manuel de Lardizabal 4, 20018 San Sebastián, Basque Country, Spain

Femtosecond and subfemtosecond time scales typically rule electron dynamics at metal surfaces. Recent advances in experimental techniques allow the experimental study of such dynamics. In this talk we shall analyze electron dynamics at surfaces and nanostructures with emphasis on screening times, spin dependence of charge transfer of adsorbates and smaller system sizes. Condensed matter effects on attophysics will also be discussed.

The puzzling CDW-phase of 1T- $TiSe_2$ from a TR-ARPES point of view

T. Rohwer[1], S. Hellmann[1], G. Rohde[1], M. Kalläne[1], K. Hanff[1], C. Sohrt[1], A. Stange[1], L. Yang[1], A. Carr[2], M.M. Murnane[2], H.C. Kapteyn[2], L. Kipp[1], M. Bauer[1], and K. Rossnagel[1]

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[2] *University of Colorado and NIST, JILA and Department of Physics, Boulder, Colorado 80309-0440, USA*

The origin of the p(2×2×2) CDW phase of pristine 1*T*-$TiSe_2$, appearing below a temperature of 200 K, has remained elusive for more than three decades. The main dispute can be brought back to the question, whether the formation of the phase state is driven by electron- lattice interaction (e.g. Peierls instability or band-type Jahn-Teller effect [1, 2]) or by a purely electronic mechanism (excitonic insulator scenario [3]). Pump-probe spectroscopy techniques provide the required sensitivity to address this problem as they enable one to disentangle - via temporal discrimination - the relevant contribution of electronic and lattice degrees of freedom. A most direct access to ultrafast electronic processes in solids, such as for instance the formation or destruction of phase characteristic band gaps, is possible by time- and angle-resolved photoelectron spectroscopy (TR-ARPES) [4]. By the application of ultrashort probe pulses in the XUV spectral regime we recently succeeded to extend the momentum regime accessible by this technique to values exceeding the typical size of a Brillouin zone [5]. The approach particularly enabled us to identify and monitor an extremely fast photo-induced melting of the CDW phase of 1*T*-$TiSe_2$.

In this contribution we will report on the most recent progress of our TR-ARPES studies on 1*T*-$TiSe_2$. Based on a comparing study with other compounds out of the class of transition metal dichalcogenids we were able to set up a characteristic hierarchy of melting times of electronic order parameters [6]. The systematics of this approach provides conclusive evidence for the existence of the excitonic insulator phase in 1*T* -$TiSe_2$.

[1] K. Rossnagel, L. Kipp, and M. Skibowski, Phys. Rev. B 65, (2002) 235101.

[2] T.E. Kidd, T. Miller, M.Y. Chou, and T.C. Chiang, Phys. Rev. Lett. 88, (2002) 226402.

[3] H. Cercellier, et al., Phys. Rev. Lett. 99, (2007) 146403.

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

[5] T. Rohwer, et al., Nature 471, (2011) 490.

[6] S. Hellmann, et al., Nature Comm. 3, (2012) 1069

Luttinger liquid universality in the time evolution after an interaction quench

C. Karrasch[1], J. Rentrop[2], D. Schuricht[2], V. Meden[2]

[1]*Department of Physics, University of California, Berkeley, USA*

[2]*Institut für Theorie der Statistischen Physik, RWTH Aachen University, Germany*

We provide strong evidence that the relaxation dynamics of one-dimensional, metallic Fermi systems resulting out of an abrupt amplitude change of the two-particle interaction has aspects which are universal in the Luttinger liquid sense: The leading long-time behavior of certain observables is described by universal functions of the equilibrium Luttinger liquid parameter and the renormalized velocity. We analytically derive those functions for the Tomonaga-Luttinger model and verify our hypothesis of universality by considering spinless lattice fermions within the framework of the density matrix renormalization group [1,2].

[1] C. Karrasch, J. Rentrop, D. Schuricht, and V. Meden, Phys. Rev. Lett. 109, 126406 (2012)

[2] J. Rentrop, D. Schuricht, and V. Meden, New J. Phys.14, 075001 (2012)

Dynamics of correlated electrons and phonons after sudden excitations

Marco Schiro'[1]

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Transient time dependent phenomena in strongly correlated systems are attracting a great deal of interest in a number of different physical contexts, ranging from ultracold atomic gases to pump probe experiments n correlated materials. Indeed when brought far from equilibrium by extensive energy perturbations strongly correlated electron systems can display non trivial dynamical behaviours or even be trapped into long lived metastable states that differ substantially from their low-energy counterparts. In this talk I will focus on the single band Hubbard Model and show that physical properties of these metastable states, including possible short-time crossovers or dynamical transitions, can be captured by a Gutzwiller time dependent variational approach [1]. As opposite, the long time dynamics where relaxation and thermalization will eventually arise crucially requires coupling to quantum fluctuations. I will discuss how these can be included using different theoretical approaches, including slave-spins [2] and non-equilibrium DMFT [4]. Finally, I will comment on the role of lattice degrees of freedom and surface effects on the non equilibrium dynamics of the Hubbard Model induced by sudden excitations such as those realized in modern pump-probe experiments[3].

[1] M. Schiro', M. Fabrizio, PRL 105 076401 (2010)

[2] M. Sandri, M. Schiro', M. Fabrizio, PRB 86, 075122 (2012)

[3] P. Andre', M. Schiro', M. Fabrizio, PRB 85, 205118 (2012)

[4] M. Schiro', (in preparation)

Optical magnetization control in EuO films

Manfred Fiebig[1]

[1]*ETH Zurich, Department of Materials, Wolfgang-Pauli-Strasse 10, 8093 Zurich, Switzerland*

The technology for the growth of thin oxide films or heterostructures is approaching the level of atomic control achieved with semiconductors. Yet, in contrast to semiconductors, strong electron correlations lead to novel and sometimes exotic states within the constituents or at its interfaces. The variety of accessible states is further enriched by entering the realm of nonequilibrium phenomena. For example, optical pumping can promote or control magnetism or induce transitions from insulating to conducting phases.

I will begin my talk with an introduction into optical control of ordered states in ordered films and at interfaces and how to detect it by time-resolved nonlinear optical spectroscopy. As a model case the ultrafast optical manipulation of magnetic order in epitaxial EuO films will then be discussed. EuO is a very prominent candidate for spintronics applications because of its relatively high ordering temperature, the nearly perfect spin polarization and the possibility to grow it as spin injector on silicon. I will show that the ferromagnetic state in epitaxial EuO films can either be enhanced or attenuated by optical control on the sub-picosecond time scale. The key to this control is the manipulation of the exchange coupling by carrier excitation across the 4f-5d gap. The optical modification of the magnetization will be quantified by comparing the effects of optical and chemical carrier doping, the latter via Gd substitution. A theory backing up and expanding our experimental results will be presented in the talk by J. Kroha.

Ab initio theory for ultrafast dynamics in two-and three-magnetic-center molecules

Wolfgang Hübner[1], Georgios Lefkidis[1], Wei Jin[1], Hongping Xiang[1,2]

[1]*Department of Physicsand Research Center OPTIMAS, University of Kaiserslautern,P. O. Box 3049, D-67653 Kaiserslautern, German*

[2]*Department of Physics and Astronomy, California State University Northridge, Northridge, California 91330-8268, USA*

Using *ab initio* quantum theory we obtain the ground and the lower excited states of small magnetic molecules. To account for the strong correlations we use the symmetry-adapted-cluster configuration-interaction (SAC-CI) method, followed by the perturbative inclusion of spin-orbit coupling (SOC) and a static, external magnetic field. After calculating the electronic, magnetic and phononic properties of every state and in order to coherently manipulate the magnetic state of our systems, we propagate the wavefunctions in time under the influence of a laser pulse. We optimize the pulse with a dedicated genetic algorithm.

We calculate the 120 lowest electronic states of Ni3Na2and find a strong phonon-magnon coupling, which leads to the existence of magnetic phases (Fig. 1a,b). At the same time we derive several laser-induced spin-flip scenarios, thus unifying the ultrafast intraphase, SOC-mediated and the slow interphase, phonon-mediated magnetic switching[1].We also perform calculations on the recently synthesized complex[NiII2(L-N4Me2)(emb)]and predict a local, ultrafast spin-flip scenario involving charge-transfer states. We characterize the relevant, transient electronic states and compare with dynamic experimental data(Fig. 1c,d)[2].

This work was done with the financial support of the Carl-Zeiss Foundation and the German Research Foundation through the Collaborative Research Center SFB/TR 88 "3MET".

[1] H. P. Xianget al., Phys. Rev. B 86, 134402 (2012)

[2]W. Jinet al., Phys. Rev. Lett. (2012) (in press)

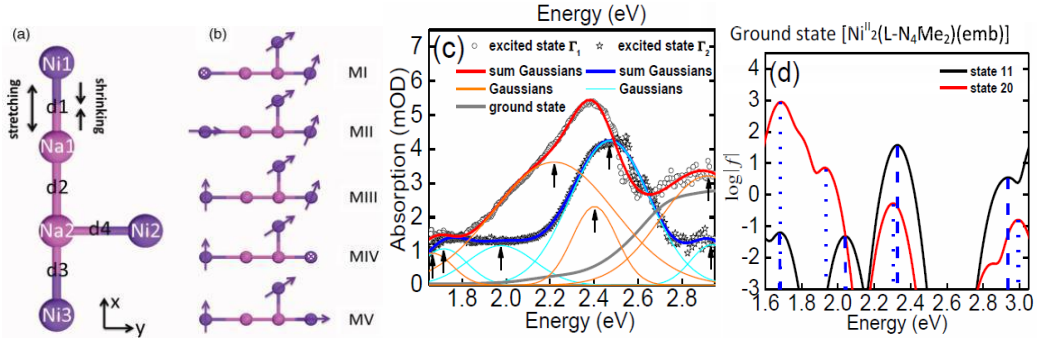

Fig. 1Magnetic phases of $Ni_3Ni_2$and absorption spectra of [Ni_{II2}(L-N_4Me_2)(emb)]

Exploring ultrafast magnetism with X-rays and THz radiation

I. Radu[1], C. Stamm[1], A. Eschenlohr[1], K. Vahaplar[2], T. Kachel[1], N. Pontius[1], R. Mitzner[1], K. Holldack[1], A. Föhlisch[1], F. Radu[1], R.F.L.Evans[3], T. A. Ostler[3], J. Mentink[2], R. W. Chantrell[3], A. Tsukamoto[4], A. Itoh[4], A. Kirilyuk[2], A.V. Kimel[2] and Th. Rasing[2];
S. Mährlein[5], M. Wolf[5], M. Gensch[6], T. Kampfrath[5]

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The way the magnetization responds to an ultrafast, external stimulus is at the forefront of modern research in ultrafast magnetism. The use of femtosecond laser pulses proved to be an indispensable tool in ultrafast magnetization dynamics studies as one can directly address the microscopic interactions governing the magnetic ordering, e.g. the exchange and spin-orbit interactions, as well as the elementary spin excitations.

Here, we present our latest studies on ultrafast magnetism, which reveal highly unexpected and sometimes counterintuitive results by employing a novel experimental approach combining the fs laser excitation with an ultrafast, element-specific X-ray probing of spins. In particular, we demonstrate that *ultrafast magnetization switching* of an *antiferromagnetically coupled* GdFe alloy occurs via an energetically unfavorable *transient ferromagnetic state* [1], the system evolving against the ground state exchange interaction. Moreover, an unexpected dynamic decoupling of the magnetic moments has also been observed in classical *ferromagnetic* FeNi alloy [2] despite the strong exchange interaction that couples them. These results provide evidence for a demagnetization/switching speed that scales with the magnitude of the elemental magnetic moment and varies with the symmetry of the exchange interaction. As such, one can use these observations as a recipe to tweak the switching times in a large class of magnetic materials and thus to design novel materials with optimized, tailor-made switching properties.

In order to identify and disentangle the various quasiparticles (e.g. phonons, magnons) that are driving the ultrafast magnetization dynamics on such ultrashort timescales, we follow a novel research line aiming at a *resonant, direct and selective pumping of quasiparticles using THz/mid-IR radiation and X-ray probing.* Here I will present our ongoing activities along these lines showing our first results on THz-driven dynamics of magnetic oxides.

[1] I. Radu et. al., *Nature* 472, 205 (2011); *Proc. SPIE* 8260, 82601M (2012).

[2] I. Radu et. al., (submitted).

A hybrid time-dependent numerical renormalization group approach for strongly correlated quantum impurity systems

Frithjof Anders
Theoretische Physik II, Technische Universität Dortmund, 44221 Dortmund, Germany

The description of quantum systems out of equilibrium is one the fundamental challenges in theoretical physics. We present a hybrid approach to nonequilibrium dynamics of quantum impurity systems. The numerical renormalization group serves as a means to generate a suitable low-energy Hamiltonian, allowing for an accurate evaluation of the real-time dynamics of the problem up to exponentially long times using primarily the time-adaptive density-matrix renormalization group. We extract the decay time of the interaction-enhanced oscillations in the interacting resonant-level model and show their quadratic divergence with the interaction strength U. Our numerical analysis is in excellent agreement with analytic predictions based on an expansion in 1/U. An outlook to application of the TD-NRG to quantum-transport through nano-devices is given.

Quench dynamics in one-dimensional massive field theories: Ising field theory and sine-Gordon model

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[2]*University of Oxford, The Rudolf Peierls Institute for Theoretical Physics, OX1 3NP Oxford, United Kingdom*

We study [1] the real-time dynamics of the order parameter $\langle\sigma(t)\rangle$ in the Ising field theory after a quench in the fermion mass, which corresponds to a quench in the transverse field of the corresponding transverse field Ising chain. The long-time behavior is obtained analytically by a resummation of the leading divergent terms in a form-factor expansion for $\langle\sigma(t)\rangle$. We develop a method for treating divergences associated with working directly in the field theory limit. We recover the scaling limit of the corresponding result obtained for the lattice model [2]. In the second part we generalize our formalism to other integrable models, notably the sine-Gordon model describing interference experiments on Bose condensates. In particular, we focus on the effects of the initial state and the locality of the considered operators on the dynamics after a quantum quench.

[1] D. Schuricht and F. H. L. Essler, J. Stat. Mech. (2012) P04017.

[2] P. Calabrese, F. H. L. Essler, and M. Fagotti, Phys. Rev. Lett. 106, 227203 (2011).

Correlation dynamics in ultracold atomic gases

C. Kollath[1]

[1]*University of Geneva, 24, Quai Ernest Ansermet, 1211 Geneva, Switzerland*

Atomic gases cooled to Nanokelvin temperatures are a new exciting tool to study a broad range of quantum phenomena. In particular, an outstanding degree of control over the fundamental parameters, such as interaction strength, spin composition, or dimensionality has been achieved. This has facilitated access to strongly correlated quantum many body physics in exceptionally clean samples. For example, artificial periodic structures for the atomic gas can be created using laser light to mimic condensed matter systems. Further, the outstanding tunability of cold gases allows to rapidly change the system parameters and to observe the subsequent quantum evolution. This ability is unmatched in conventional solid state samples and poses new challenges for the understanding of quantum dynamics in correlated many-body systems. I will report on recent progress on investigating fermionic and bosonic gases in optical lattices under the influence of controlled dissipative coupling. One focus will be the question of how in a repulsively interacting fermionic gas, coherence between pairs of fermions can emerge by local coupling to an incoherent environment.

Spatiotemporal buildup of correlations in the Kondo model

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[2]*Physics Department, Ludwig-Maximilians University München, Theresienstr. 37, 80333 München, Germany*

A quintessential feature of many correlated electron systems is the screening of magnetic moments through conduction band electrons. This physical process is typically described with the Kondo model. In a non-equilibrium setting where the impurity spin is initially decoupled from the conduction band, it is interesting to investigate how this screening builds up as a function of space and time. We study this problem at the exactly solvable Toulouse point of the Kondo model and derive analytic results which are expected to be generic in the whole Kondo regime. Specifically, we show how the impurity spin is transported to infinity in the conduction band and how screening builds up in the wake of this process. An important difference to equilibrium physics becomes apparent when comparing the non-equilibrium impurity spin-conduction band spin susceptibility with the respective correlation function: The susceptibility builds up causally within a light cone given by the Fermi velocity, while correlations build up immediately even outside the light cone with an algebraic decay at zero temperature. This is due to the entangled nature of the Fermi gas ground state in a position basis. An exponential decay outside the light cone is found for nonzero temperature.

Theory for pump/probe experiments in charge-density-wave systems

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[2]*Centre for Condensed Matter Theory, Department of Physics, Indian Institute of Science, Bangalore, 560012, India and Condensed Matter Theory Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560064, India*
[3]*Stanford Institute for Materials and Energy Science, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, U.S.A. and Geballe Laboratory for Advanced Materials, Stanford University, Stanford, CA 94305, U.S.A.*

In this presentation I will discuss two topics that we have recently addressed with an exact solution of the nonequilibrium problem for a two-sublattice charge-density-wave system. The first is a theory for pump/probe time-resolved photoemission spectroscopy, where we find a partial decoupling of the order parameter from the gap in the density of states for the transient state created during and shortly after the pump is applied. This behavior agrees with the behavior seen in recent experiments on tanatalum dichalcogenides [1,2] and on rare-earth tritellurides [3]. Second, we will discuss the fundamental question of what primarily determines the ability of an external excitation to pump energy into a quantum system? In particular, is it dominated by the frequency of the driving field, or its amplitude, or is there a crossover from one to another? We use a simple Peierls' substitution to describe the electric field in a vector-potential-only gauge, and solve the problem exactly by evaluating the appropriate 2x2 evolution operators for each momentum point in the reduced Brillouin zone. This approach allows us to examine these systems with high numerical accuracy and for times much longer than can be reached with other current nonequilibrium solvers.
Different parts of this work were supported by the NSF under grants numbered DMR-1006605 and OCI-0904597, by the US DOE under grants numbered DE-FG02-08ER46542, DE-AC02-76SF00515 and DE-FG02-08ER46540, by the Indo-US Science and Technology Forum under the centre grant JC-18-2009 Ultracold atoms, and from the Indian DST.

[1] L. Perfetti, et al., Femtosecond dynamics of electronic states in the Mott insulator 1T-TaS_2 by time resolved photoelectron spectroscopy, New J. Phys. 10, 053019 (2008).

[2] S. Hellmann,et al., Ultrafast Melting of a Charge-Density Wave in the Mott Insulator 1T-TaS_2, Phys. Rev. Lett. 105, 187401 (2010).

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Density-matrix theory for time-resolved dynamics of superconductors in non-equilibrium

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We study the ultrafast dynamics of unconventional superconductors from a microscopic viewpoint employing density-matrix theory. In particular, we derive and solve numerically equations of motions which allow calculating the resulting oscillations of the superconducting order parameter exactly. In a next step we study the role of phonons in the non-equilibrium state. The dynamics of coherent phonons after excitation with a short intense pump pulse can be treated at a fully quantum kinetic level. We find that in the nonadiabatic regime the generation of coherent phonons is resonantly enhanced when the frequency of the order parameter oscillations is tuned to the phonon energy which might be achieved by changing the pump pulse intensity [1]. In the case of incoherent phonons we use a cluster expansion method to derive the resulting damping [2]. Our Boltzmann-type calculations for the ultrafast dynamics are then partly able to describe recent pump-probe Raman scattering experiments in high-Tc cuprates [3]. Finally, motivated by recent time-resolved experiments in the pnictides, we extend our theory to 2-band superconductors and study the characteristic changes of the oscillations of the superconducting gaps due to interband coupling. [4].

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Theory for time-domain photon spectroscopy

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In this talk I will present some recent work concerning the development of theories for time-domain photon spectroscopies, with a focus on studying non-equilibrium pump-probe dynamics. Studies of several model systems will be presented, including non-equilibrium dynamics across of metal-insulator transition in correlated systems, strong electron-phonon interactions, and spectral properties in a charge density wave state. The similarities and differences between equilibrium dynamics will be highlighted [1].

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Dynamics of topological surface states on topological insulators investigated by time-resolved two-photon photoemission

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Topological insulators are characterized by symmetry-induced metallic surface states with a chiral spin structure. The dynamics of topological surface states has been studied on p-doped bismuth chalcogenide samples by time-resolved angle-resolved photoemission [1,2]. On a series of natively n-doped bismuth chalcogenides ($Bi2Se_3$, $Bi2Te_2Se$, Bi_2Te_3) we recently found by two-photon photoemission (2PPE) additional linearly-dispersing topological surface states about 1.4 eV above the conventional topological surface states [3]. Circular dichroism measurements show the expected helical spin structure which proves that these states are topological surface states in agreement with theoretical calculations.

The dynamics of these states has been measured by time-resolved 2PPE. A careful analysis of the data which are overlapped by contributions from an image-potential states yields lifetimes around 20 fs. The image-potential state has a lifetime of 25 fs.

The conventional topological surface state has been studied by 2PPE for the p-type antimony/tellurium-based topological insulator $SnSb_2Te_4$. The energy is located 0.31 eV above the Fermi level. The dynamics of the state observed by time-resolved 2PPE is dominated by filling of the the state from the lowest bulk conduction band spanning a time scale of 300 fs. Data analysis based on a rate equation model gives lifetimes around 40 fs for the topological surface state.

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Coherent phonons in one-dimensional atomic chains: Bi(114)

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As a consequence of the broken inversion symmetry at surfaces, Kramer's degeneracy no longer holds and the surface electronic bands are no longer spin degenerate. This so-called Rashba splitting scales with the strength of the spin-orbit interaction [1] and is large for heavy elements [2].

Recently, almost perfectly one-dimensional atomic rows were discovered on Bi(114) [3]. The Fermi line corresponding to the Fermi surface of the surface state is spin split as shown by spin-resolved photoelectron spectroscopy [3] and circular dichroism in the angular distribution [4]. The electron-electron scattering rates are extremely low due to the low density of states close to the Fermi level and due to the spin splitting of the surface states, resulting in surprisingly long lifetimes. Due to the Fermi surface topology the electronic system is instable against the formation of a charge-density wave accompanying a period lattice distortion.

In this talk we will present recent data taken from Bi(114) by means of time-resolved one- and two-photon photoemission. The hot electron gas, the lifetimes of which are found to be in the picosecond range, exhibit energy and intensity oscillations due to the excitation of coherent phonon modes [4]. Beside the well-known bulk phonon A_{1g} [5], a second mode was observed to modulate bulk and surface states of this 1D metal. In comparison with bulk phonon calculations [6], the mode could be identified as low-energy optical phonon with infinite wavelength, which generates a standing wave along the atomic chains.

No modes were observed, which would introduce new periodicities in the atomic rows and potentially cause a charge-density wave transition to an insulating state. Apparently, the spin-splitting of the surface states inhibits a nesting of the Fermi surface and, thereby, the stabilization of a standing charge-density wave.

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Charge recombination in photoexcited Mott-Hubbard insulator

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Recent femtosecond pump-probe experiments on Mott-Hubbard insulators reveal charge recombination and thermalization which is in the picosecond range, much faster than in clean band-gap semiconductors although the excitation gaps in Mott-Hubbard insulators are larger. We present a calculation of the recombination rate of the excited holon-doublon pairs based on the model relevant for undoped cuprates which shows that such fast processes can be explained even quantitatively with the multi-magnon emission. The precondition is the existence of the Mott-Hubbard bound exciton of the s-type. We _nd that its decay is exponentially dependent on the Mott-Hubbard gap and on the magnon energy, with a small prefactor which can be traced back to strong correlations and consequently large exciton-magnon coupling. Time evolution of the optical response during the charge relaxation and recombination will be also considered.

Equilibration versus thermalisation in the Bose & Fermi Hubbard model

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For the Bose & Fermi Hubbard model at vanishing initial temperature, we study the quantum dynamics after a sudden quench from zero to finite hopping rate (within the Mott insulator regime).After some damped oscillations, the on-site probabilities and the off-site correlations settle down to a quasi-equilibrium state. Even though the on-site probabilities can be described by a thermal state with some temperature, the correlations do not correspond to this temperature, i.e., the quasi-equilibrium state is not thermal. Real thermalisation (if it occurs) requires much longer time scales.

Optical control in quantum solids

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In this talk I will discuss some of our recent work aimed at controlling the low-lying excitations of quantum solids using strong field transients in the mid-infrared and THz regime. I will cover the excitation of selected vibrational resonances to manipulate the many-body physics of Mott Hubbard Insulators and to perturb competing orders in High-Tc superconductors. Finally, I will show how the electrodynamics of layered superconductors can be driven through the order-parameter phase gradient, demonstrating ultrafast transistor action in a layered superconductor. Technical advances in the use of coherent optics, from tabletop sources to THz and X-ray Free Electron Lasers will also be discussed.

Correlated electron and lattice dynamics in ionic materials spatially resolved by ultrafast x-ray diffraction

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Numerous functional processes in condensed matter involve atomic motions and charge relocations on ultrashort time scales. X-ray diffraction methods with a femtosecond time resolution allow for spatially resolving transient structures and charge distributions in a most direct way, providing new insight into the structure-function relationship of crystalline materials. In particular, transient x-ray powder diffraction patterns allow for deriving time-dependent electron density maps [1]. In this talk, recent results on ultrafast electron and lattice motions in ionic crystals are presented. Experiments are based on a pump-probe approach in which an optical excitation pulse initiates structural dynamics and a hard x-ray pulse from a synchronized laser-driven plasma source is diffracted from the excited powder sample [2,3]. Such measurements reveal the interplay of lattice and charge motions in the photoexcited prototype material KDP (KH_2PO_4) [4]. Upon elongation of the soft mode, a low-frequency lattice vibration, electrons are relocated over the length of a PO bond which is 100 times larger than the vibrational amplitude. As a second example, the field-driven transfer of valence electrons between ions in a superposition of quantum states will be addressed for the materials of $LiBH_4$ [5] and LiH. In $LiBH_4$, the strong external field provided by a sub-40 fs laser pulse at frequencies far below the bandgap drives an interionic transfer of electronic charge from the $(BH_4)^-$ to the Li^+ ion, i.e., over a distance of some 250 pm. This fully reversible transfer mechanism makes a major contribution to the overall optical polarizability of the material.

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Dual-Fermion approach to non-equilibrium strongly correlated problems

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We present a generalization of the recently developed dual fermion approach introduced for correlated lattices to non-equilibrium problems. In its local limit, the approach has been used to devise an efficient impurity solver, the superperturbation solver for the Anderson impurity model. Here we show that the general dual perturbation theory can be formulated on the Keldysh contour. Starting from a reference Hamiltonian system, in which the time-dependent solution is found by exact diagonalization, we make a dual perturbation expansion in order to account for the relaxation effects from the fermionic bath. Simple test results for closed as well as open quantum systems in a fermionic bath are presented.

Dynamics of correlated spins on the timescale of the exchange interaction

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The correlation between spins in magnetic materials is determined by the exchange interaction, the strongest force in magnetism. Understanding spin dynamics in magnetic materials is an issue of crucial importance for progress in information processing and recording technology. However, rather little is known about the behavior of correlated spins directly after being excited on a timescale equivalent to or faster than that corresponding to the exchange interaction (10–100 fs), that is, in a non-adiabatic way. After the first demonstration of ultrafast laser-induced demagnetization in ferromagnetic nickel [1], many intriguing observations have been reported on magnets with multiple magnetic sublattices, including ultrafast changes of the anisotropy [2] and magnetization reversal [3]. Nevertheless, the theoretical understanding of ultrafast laser-induced spin dynamics is still a challenge. In particular, so far the role of the exchange coupling between different magnetic sublattices has as not been studied thoroughly. In this contribution we present a general theoretical framework for the analysis of ultrafast longitudinal spin dynamics in multi-sublattice magnets [4]. We distinguish relaxation of relativistic and exchange origin and show that when the former dominates, non-equivalent sublattices have distinct dynamics despite their strong exchange coupling. Even more interesting, in the exchange dominated regime sublattices can show highly counter-intuitive transitions between parallel and antiparallel alignment. Moreover, our theory predicts that exchange relaxation enhances the demagnetization speed of both sublattices only when they are antiferromagnetically coupled.

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Numerical schemes for time-propagation of strongly correlated systems

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Numerical solution of the time-dependent Schrödinger equation involves several (explicit or implicit) algorithmic choices, which determine the accuracy and efficiency of the calculation. Within the context of exact diagonalization, time propagation essentially reduces to the computation of matrix exponentials but remains a difficult problem due to the huge dimension of a many-particle Hilbert space.

We will discuss algorithmic solutions for (i) the computation of matrix exponentials via Chebyshev techniques, (ii) the computation of the propagator for a time-dependent Hamiltonian using variants of the Magnus expansion, (iii) the efficient encoding of quantum states in reduced Hilbert spaces, and illustrate their use with applications to strongly correlated systems out of equilibrium.

Nonthermal symmetry-broken states in the Hubbard model

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Strong perturbations of the antiferromagnetic phase of the Hubbard model, e.g., by means of interaction quenches or photo-excitation, can induce a melting of the long-range order. However, even when the excitation density exceeds the energy that would be needed to heat the system above the Neel temperature, long-range order can persist for very long times. In the talk, the nature of these long-lived non-thermal broken symmetry states is discussed for both weak [1] and strong interaction [2]. In the strongly interacting case, symmetry-broken states exist due to the long-lifetime of charge excitations (doublon-hole pairs). At weak interaction, on the other hand, the observed behavior can be understood qualitatively from a time-dependent Hartree Fock calculation, within which the (paramagnetic) thermal equilibrium state is not accessible either. When the excitation density is further increased above a threshold value that is typically larger than the energy that would be needed to bring the system to Neel temperature, long-range order disappears on very short timescales. The transition between (non-thermal) symmetry broken states and (non-thermal) paramagnetic states shows signatures of nonequilibrium critical behavior. Implications of these results for other types of order, such as superconductivity and charge order, are discussed.

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Coherent trajectories through phase transitions in layered chalcogenides and related systems.

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Multipulse methods in femtosecond spectroscopy can be used to study the *coherent evolution* of single particle and collective excitations through symmetry breaking transitions. The first example of such as study was performed on $ReTe_3$ (Re=Rare earth) materials, 2-dimensional charge-density-wave (CDW) materials where the collective amplitude mode excitations were followed through the CDW transition. Of particular interest are the topological excitations – domain walls – which are created at the transition by the Kibble-Zurek mechanism, and their coherent evolution with time. Using specially designed experiments, the coherent annihilation of topological defects can be observed as distortions of the AM lineshape appearing when order-parameter waves emitted after topological defect annihilation events reach the surface of the crystal. Such behavior is found to be common in some rare-earth telluride and some transition metal selenide CDW systems. Of particular interest are transitions to new hidden states of matter, which can only be reached under non-equilibrium conditions. In particular, a new *stable* hidden state of the well known chalcogenide TaS_2 is found[2]. We demonstrate bistable switching to and from the hidden state with ultrashort laser pulses and discuss its origin in terms of a strongly correlated ordered state created through the Kibble-Zurek mechanism. A brief comparison with the system trajectory through the superconducting transition will be discussed.

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Theory for tuning the ultrafast magnetic dynamics in Gd-Doped EuO

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EuO is a dense ferromagnetic semiconductor with a Curie temperature of T_C = 69 K. Upon Gd-doping, $Eu_{1-x}Gd_xO$ undergoes a simultaneous ferromagnetic and insulator-metal transition, with a resistivity drop of several orders of magnitude, making it an interesting material for spintronics applications. Recent pump-probe experiments show that resonant pumping of electrons from the Eu 4f states into the Eu 5d conduction leads to an ultrafast increase of the ferromagnetic coupling J_{eff} by creating magnetic excitons. Surprisingly, by Gd-doping J_{eff} can be tuned to further increase for low Gd concentration or to decrease for high Gd concentration. We describe $Eu_{1-x}Gd_xO$ as a Heisenberg ferromagnet (Eu 4f sublattice), coupled to a conduction (Eu 5d-6s band) band in the presence of magnetic Gd impurities and develop the theory for the ultrafast magneto-dynamics. We calculate the pump-induced non-equilibrium RKKY interaction and find oscillatory behavior and power law decay in space, with an exponent depending on the non-equilibrum distribution. The non-monotonic tuning of the effective coupling strength J_{eff} is explained semiquantitatively by a subtle interplay of the oscillatory RKKY coupling, the spectral weight shift induced by the Gd doping, and kinematic restrictions involved in the pumping process. We also discuss how to extract not only the effective magnetic coupling but also the dynamics of the magnetization from second-harmonics generation (SHG) data.

Prethermalization and thermalization of weakly interacting quantum systems

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If an isolated quantum many-body system is suddenly forced out of equilibrium, how does it relax to a new equilibrium state? Does it relax to the thermal state predicted by statistical mechanics, which depends only on energy and particle number? Indeed, integrable systems usually relax instead to a nonthermal state, because a detailed memory on the initial conditions persists due to the many constants of motion [1]. On the other hand generic, nonintegrable systems are expected to relax to a thermal state [1], as observed, e.g., for quenches to intermediate Hubbard interaction [2]. Nonetheless, the precise mechanisms and conditions for thermalization in isolated systems are still under active debate. A special situation arises for weakly interacting systems: because of the nearby integrable, noninteracting Hamiltonian they are first trapped in a so-called prethermalized state, and can thermalize only at a later stage [3]. We show that this prethermalization plateau is again due to a large number of - now only approximate - constants of motion and can be represented by generalized Gibbs ensemble [4]. As the time evolution continues, we can describe the decay of this quasistationary state and the crossover to the thermal state by a kinetic integrodifferential equation, with good quantitative agreement for quenches to small Hubbard interaction [2]. This approach provides a controlled and conceptually straightforward description of the thermalization dynamics and establishes that thermalization can occur even in the perturbative regime.

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(See also the poster by Michael Stark.)

Coherent dynamics of pairing in a superconducting nanowire

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Recent advances in ultrashort THz sources, which can produce pulses of considerable strength,[1-3] made it possible to study the low energy electromagnetic response of superconductors and to understand the excitation dynamics of high-density quasiparticles in the vicinity of the superconducting gap without heating the phonon bath. This paves the way towards experimental studies of coherent dynamics of superconducting correlations, which require sources generating pulses both shorter than the intrinsic time for superconductors, during which quasiparticles condensate, and with frequencies of the order of the superconducting gap. Experimentally this was visible so far mostly in cold atomic Fermi gases where the time-dependent pairing interaction can be readjusted almost instantaneously by magnetic field tuning through a Feshbach resonance. Recently an experimental study of the nonequilibrium BCS state dynamics by intense THz pulses in a superconducting NbN film was reported.[4] The set up used fulfills requirements necessary for the formation of the coherent dynamics.
Inspired by this experiment we address the question of the influence of quantum confinement on the pairing dynamics in clean BCS-like superconductors. We report the time evolution of a perturbation of the superconducting pairing in a nanowire in a time interval small compared to the quasiparticle relaxation time. Within the density-matrix formalism and Bogoliubov-de Gennes equations we provide a description of the coherent dynamics of the nonequilibrium superconducting pairing. The order parameter is found to be an oscillatory function of time, which attenuates asymptotically with a power law to a new equilibrium position. The exponent of the decay depends oscillatorily on the confinement strength.

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Attosecond dynamics of light absorption and refraction in fullerenes

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The collective electron response is ubiquitous and has a wide range of applications, e. g. in plasmonics or in optical devices. Here we propose a setup (Fig. 1) to trace on an attosecond time scale the birth of single and collective excitations in fullerenes [1,2]. The theory relies on combining quantum chemistry with a quantum kinetic approach for calculating the steady-state (Fig.2) as well as the attosecond time transient (Fig.3) light absorption and refraction. An analytical model elucidates the numerically calculated transient features, which serve as indicators for the emergence of collective modes. The new findings are of importance for ultrafast photonic and electronic applications.

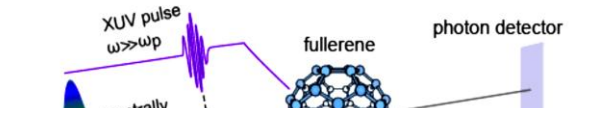

Figure 1. An attosecond XUV pulse ionizes a fullerene. After a time delay τ_D the sample absorption of a linear-polarized pulse is traced.

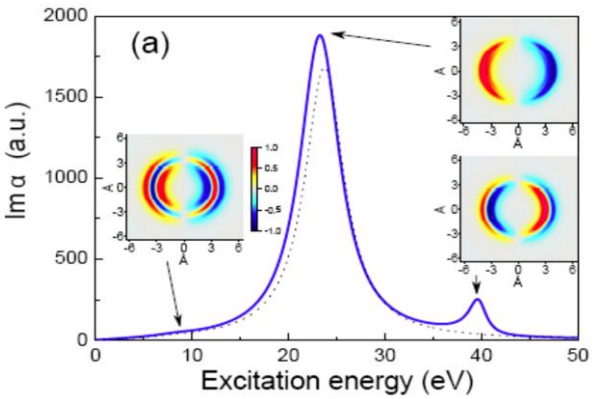

Figure 2. Energy dependence of the imaginary part of the dipolar polarizability of C_{60} in the long-time limit. Insets show the calculated spatial densities of the plasmonic modes, corresponding to the peaks in the spectrum, in any plane crossing the center of the molecule and being parallel to the polarization of the external electric field.

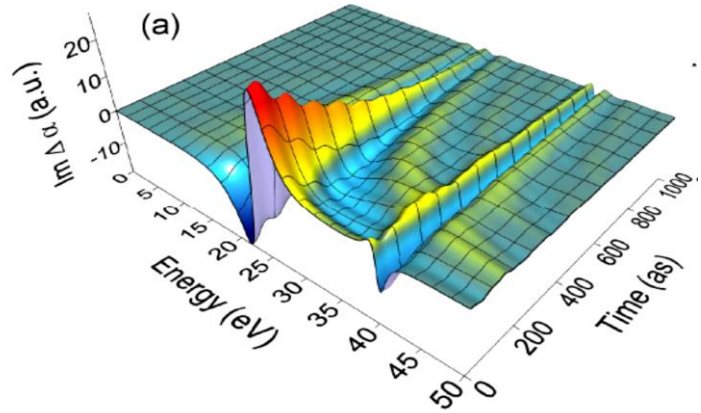

Figure 3. The energy dependence of the difference in the imaginary part of the dipolar polarizability when removing one HOMO electron of C_{60} as a function of the time delay after the removal.

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Femtosecond photodoping phenomena in cuprate high-T_c superconductors

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Ultrafast processes in high-T_c cuprate superconductors excited with femtosecond optical pulses have been intensively studied for over the last two decades [1]. Most of the work focused on dynamics in the superconducting state and the pseudogap state of the doped compounds, aiming at understanding the characteristic relaxation processes and the nature of of the glue binding the quasiparticles to form Cooper pairs. On the other hand, much less is known about the dynamics in the undoped and weakly doped (non-superconducting) compounds, despite the fact that this doping range bares an invaluable information about the bare nature of states giving rise to superconductivity in this class of materials.
Here we present time-resolved studies of dynamics of the complex optical conductivity over 0.5-2.8 eV range in undoped and weakly doped antiferromagnetic (AFM) charge-transfer isolator $La_{2-x}Sr_xCuO_4$. By performing systematic studies as a function of temperature, excitation photon energy and density, and by applying standard models for analysis of optical spectra important information about the nature of the low energy excitations in undoped and weakly doped cuprates was gained. We demonstrate that following Cu-O charge transfer excitation the holes trap with probability close to one to form magnetic polarons. This process saturates at excitation densities corresponding to 1-2 % doping, the doping level where long-range AFM order disappears, suggesting the transition to a transient correlated polaronic state. Finally, despite the fact that the long-range AFM order is suppressed at 1-2% doping, we find no evidence of photoinduced metallicity even for excitation densities corresponding to 15 % doping, demonstrating the robustness of the AFM ground state against photodoping.

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In search for the pairing glue in cuprates by non-equilibrium optical spectroscopy

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In strongly-correlated electron materials the electronic and optical properties are significantly affected by the coupling of fermionic quasiparticles to different degrees of freedom, such as lattice vibrations and bosonic excitations of electronic origin. Broadband ultrafast spectroscopy [1] is emerging as the premier technique to unravel the subtle interplay between quasiparticles and electronic or phononic collective excitations, by their different characteristic timescales and spectral responses. By investigating the femtosecond dynamics of the optical properties of prototypical copper oxides (Y-Bi2212) over the 0.5-2 eV energy range, we disentangle the electronic and phononic contributions to the generalized electron-boson Eliashberg function [2], showing that the spectral distribution of the electronic excitations, such as spin fluctuations and current loops, and the strength of their interaction with quasiparticles can account for the high critical temperature of the superconducting phase transition [3]. Finally, we discuss how the use of this technique can be extended to the underdoped region of the phase diagram of cuprates, in which a pseudogap in the quasiparticle density of states opens.

The microscopic modeling of the interaction of ultrashort light pulses with unconventional superconductors will be one of the key challenges of the next-years materials science, eventually leading to the full understanding of the role of the electronic correlations in controlling the dynamics on the femtosecond timescale.

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[2] J.P. Carbotte et al. *Rep. Prog. Phys*. **74** 066501 (2011)
[3] S. Dal Conte et al. *Science* **335** 1600 (2012)

Probing the non-equilibrium momentum dependent dynamic of high temperature superconductors by time-resolved photoemission spectroscopy

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Understanding how superconductivity emerges from other competing phases and how this balance evolves through the phase diagram is one of the biggest challenges in the field of high Tc superconductors. By using high resolution time- and angle- resolved photoemission spectroscopy (tr-ARPES) we are able to directly probe the effects of optical excitation on the electronic structure of cuprate superconductors, and study the resulting quasiparticles, superconducting gap, and Cooper pair formation dynamics near their natural time- scales. Direct measurements of these and other non-equilibrium spectral phenomena through the phase diagram further illustrate the power of this unique time- and momentum-resolved spectroscopy. These results reveal new windows into the nature of the pairing interaction in high Tc superconductors.

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[2] C. L. Smallwood et al. Science **336**, 1137 (2012)

[3] W. Zhang et al. In preparation

Elementary dynamics of quantum correlations in solids studied via Ultrabroadband Terahertz technology

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Few-cycle electromagnetic waveforms can now be generated covering almost the entire infrared spectral range, with amplitudes up to 1 V/Å [1]. In addition, ultrabroadband electro-optic sampling gives direct access to the light field [2]. Using these tools, we analyze the elementary quantum dynamics of low-energy degrees of freedom in condensed matter.

Studies on the buildup of screening and phonon-plasmon coupling in weakly correlated semiconductors serve as an introduction [3]. We then explain the ultrafast nature of a photoinduced insulator-metal phase transition in VO_2 via close inspection of the interplay between electronic system and the crystal lattice [4]. Current work focusses on high-Tc materials like optimally doped cuprates [5]. Recently, we discovered surprising signatures indicating an effective coupling between coherent lattice motion and the spin system in an undoped parent compound of pnictide superconductors [6].

As an outlook, coherent experiments with nonlinear excitation directly in the terahertz regime will be featured. Lead-off examples include control of a magnon mode in antiferromagnetic NiO [7] and terahertz four-wave-mixing measurements in InSb [8].

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[2] C. Kübler et al., Appl. Phys. Lett. **85**, 3360 (2004)

[3] R. Huber et al., Nature **414**, 286 (2001); Phys. Rev. Lett. **94**, 027401 (2005)

[4] C. Kübler et al., Phys. Rev. Lett. **99**, 116401 (2007)

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

[6] K. W. Kim et al., Nature Materials **11**, 497 (2012)

[7] T. Kampfrath et al., Nature Photon. **5**, 31 (2011)

[8] F. Junginger et al., Phys. Rev. Lett. **109**, 147403 (2012)

Posters

Theory of nonequilibrium dynamics of multiband superconductors

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We study the nonequilibrium dynamics of multiband BCS superconductors subjected to ultra-short pump pulses. Using density-matrix theory, the time evolution of the Bogoliubov quasiparticle densities and the superconducting order parameters is computed as a function of pump pulse frequency, duration, and intensity. Focusing on two-band superconductors, we consider two different model systems. The first one, relevant for MgB2, describes two-band superconductors with dominant intraband interactions and an attractive but weak interband pair scattering V12. The second model, relevant for iron-based superconductors, deals with the opposite limit where the interband interaction V12 is repulsive and much larger than the intraband pairing terms. For ultrashort pump pulses, both of these models exhibit a nonadiabatic behavior, which is characterized by oscillations of the superconducting order parameters. We find that for nonvanishing V12, the superconducting gap on each band exhibits two oscillatory frequencies, which are determined by the long-time asymptotic values of the gaps. The relative strength of these two frequency components depends sensitively on the magnitude of the interband interaction V12. Hence, pump-probe experiments on two-band superconductors can give valuable information on the strength of the interband pair scattering V12, and thereby shed light on the microscopic pairing mechanism.

[1] A. Akbari et al., arXiv:1205.4861

Decoupled carrier dynamics in photoexcited 1*T*-TaS_2

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1*T*-TaS_2 is a quasi-two-dimensional transition metal dichalcogenide undergoing a metal-to-insulator transition below 180 K in which a commensurate charge density wave (CCDW) coexists with a Mott insulating state. Of particular interest is the photoinduced melting of this Mott-Hubbard phase which drives the system into a short-living crossover state substantially different from the high temperature metallic phase [1,2]. We performed femtosecond pump-probe photoemission experiments in the Mott-insulating phase using different pump fluences ranging from 0.1 to 1.0 mJ/cm^2. Upon laser excitation we observe a population of states above the Fermi level (E_F) and a depletion and broadening of the lower Hubbard band (LHB) peak below E_F. Our analysis reveals a temperature-dependent difference in the relaxation dynamics of the electron population above and below E_F. This points to a possible decoupling of electron- and hole-dynamics in which carrier-phonon scattering might govern the relaxation dynamics and ,thus, to an at least unconventional metallic behavior in the photoinduced state.

We acknowledge support by the DFG through BO 1823/2, /4 and the EU under grant agreement 280555 within FP7.

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[2] Dean et al., Phys. Rev. Lett. **106**, 016401 (2011)

Emergence of long distance pair coherence through incoherent local environmental coupling

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We demonstrate that the interplay between a purely local incoherent environmental coupling, effectively heating up the system, and Hamiltonian dynamics generates quantum coherence. For a repulsively interacting fermionic lattice gas initially prepared in a Mott insulating state, coupling a noise field to the local spin density produces coherent fermionic pairs. We show that the formation of pair coherence is approximately diffusive with distance, and is experimentally observed in the pair momentum distribution as the formation of a sharp feature at the zone boundary.

Optimized extreme-ultraviolet high-harmonic generation output for *tr*ARPES from correlated-electron materials

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Time- and angle-resolved photoemission spectroscopy (*tr*ARPES) using femtosecond extreme ultraviolet (XUV) light-pulses has recently emerged to a key technology for the investigation of ultrafast quasiparticle dynamics in correlated-electron materials [1-4]. However, the full potential of this technique has not yet been achieved, i.e. all so far developed technical solutions suffered from a trade-off between photon flux, energy- and time-resolution. This was because of limitations in the intrinsic high-harmonic generation (HHG) process, and because of dispersive optical elements in the XUV-beamline, which reduce photon flux but were needed to monochromatize the output of the HHG source. Here we show that a HHG process driven by short-wavelength laser light is one optimal solution for efficient femtosecond XUV *tr*ARPES with sub 30 fs time- and sub 150 meV energy-resolution.
We exploit the potential of our new experimental capabilities by repeating measurements on the charge-density wave system 1T-$TiSe_2$ (c.f. [1]). The improved energy-resolution – without any trade-off on time-resolution or XUV photon flux – does now allow us to disentangle more details in the short-time response of correlated materials to an ultrafast laser excitation.

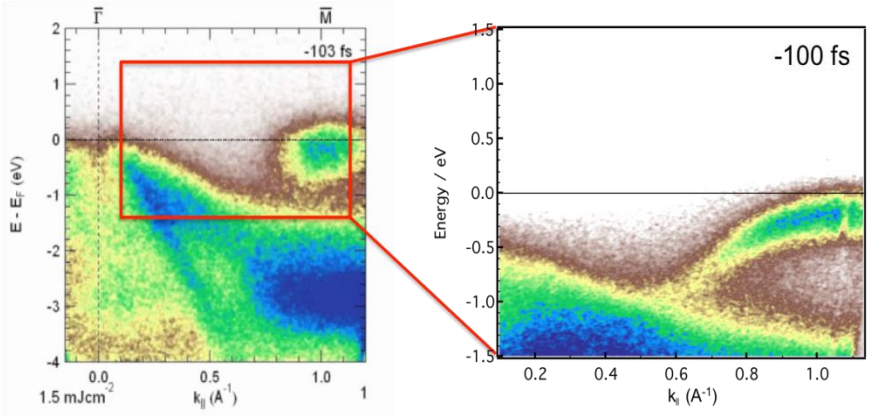

Figure 1: Comparison of photoemission maps from $TiSe_2$ as recorded with our old HHG setup (Rohwer et al., [1]), left, and after further optimization of the HHG output for an increased energy resolution (right) that is better suited for the study of correlated-electron materials.

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[2] Petersen et al., PRL 107, 177402 (2011)

[3] Carley et al., PRL 109, 057401 (2012)

[4] Hellmann et al., Nat. Comm. 3, 1069 (2012)

Ultrafast spin transport as key to femtosecond demagnetization

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Ultrafast demagnetization of ferromagnetic metals is typically triggered by excitation with a femtosecond laser pulse [1]. Here we demonstrate that hot electrons transported into a ferromagnetic layer can induce demagnetization as fast and efficient as direct laser excitation. We investigate a layered structure consisting of a Ni film covered by a Au layer, with the thickness of the Au layer chosen such that the incident laser pulse is completely absorbed. Magnetization dynamics in the buried Ni film is measured with x-ray magnetic circular dichroism in transmission geometry at the BESSY II Femtoslicing source [2], finding sub-picosecond demagnetization of equal magnitude as in a directly excited Ni film. Demagnetization of the Au-capped Ni film occurs with a time constant of 330±40 fs and its onset is slightly delayed compared to the directly excited Ni film, which demagnetizes in 140±10 fs. These experimental findings are modeled by means of superdiffusive spin transport theory [3], showing that the observed demagnetization is due to spin-dependent transport of non-equilibrium electrons from the Au layer through the ferromagnetic layer into the substrate [4].

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Integrability-based analysis of the hyperfine interaction induced decoherence in quantum dots

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Using the Algebraic Bethe Ansatz (ABA) in conjunction with a simple Monte Carlo (MC) sampling technique, we study the problem of the decoherence of a central spin coupled to a nuclear spin bath. We describe in detail the full crossover from strong to weak external magnetic field field, a limit where a large non-decaying coherence factor is found. This feature is explained by Bose-Einstein-condensate (BEC)-like physics which also allows us to argue that the corresponding zero frequency peak would not be broadened by statistical or ensemble averaging [1].

[1]. Alexandre Faribault and Dirk Schuricht, arXiv:1210.7121 (2012)

Hybrid TD-NRG and TD-DMRG method

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We present a non-equilibrium hybrid method which uses the numerical renormalization group to generate an effective low-energy Hamiltonian. This Hamiltonian is solved with the density matrix renormalization group thereby reducing drawbacks of both methods: (i) discretization errors are minimized by not using a pure Wilson chain and (ii) long time scales can be simulated even for a very large bandwidth. The validity of this method is established by comparing the results to exact results for the resonant level model. Furthermore, we find an excellent agreement between results of our hybrid method and analytic results for the interacting resonant level model in the strong coupling limit.

Relaxation of fermionic quantum systems after an interaction quench

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Due to the impressive progress on experimental side the interest in a theoretical description of non-equilibrium dynamics rose significantly. One way of taking the system into non-equilibrium are quenches, i.e. sudden changes in the intrinsic system parameters.

Thus we investigate the behavior of fermionic systems after an interaction quench, where the interaction between particles is suddenly turned on. We investigate the momentum distribution of 1D and 2D Hubbard models.

In our approach we find surprising correspondence between results for the 1D model and the $D = \infty$ DMFT results in the case of large interaction strengths. Surprisingly the 1D results can only partially be understood by bosonization.

The technique used is a semi-analytic approach based on the Heisenberg equations of motion [1]. We aim at a description of the behavior on short and intermediate time scales i.e. the prethermalization regime.

Besides the momentum distribution the method allows for a discussion of other observables for various dopings as well as the influence of different temperatures on the relaxation.

[1] G.S. Uhrig Phys. Rev. A 80, 061602(R)

Continuous frequency multiplication in a strongly driven modulated nanowire

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High-order harmonic generation in a bulk solid strongly driven by a few-cycle pulsed infrared laser has recently been observed[1]. We consider the possibility of observing an analogous effect using a continuously driven, single-band one-dimensional metal. In the absence of phonon scattering, the quantum efficiency of frequency tripling for such a system can be as high as 93%. Combining the Floquet quasi-energy spectrum with the Keldysh Green's function technique, we derive the quantum transport equation for strongly and rapidly driven electrons in the presence of weak scattering by phonons. The power absorbed from the driving field is continuously dissipated by phonon modes, leading to a quasi-equilibrium in the electron distribution. We assume terahertz frequency range, and use the Kronig-Penny model with varying effective mass to establish dimensions and modulation periodicity of an InAs/InP nanowhisker. Driving such nanowhiskers could lead to efficient third and higher-harmonic generation.

[1] S. Ghimire et al., Nature Physics 7, 138 (2011)

Dynamical quantum phase transitions for quenches in the transverse-field Ising model

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An equilibrium phase transition indicates a sudden change in the properties of a large system. For temperature-driven phase transitions this is related to nonanalytic behavior of the free energy density at the critical temperature. It will be shown that a close analogue of this behavior can occur generically in the real-time evolution of quantum systems, namely non-analytic behavior at a critical time [1]. Such a behavior will be called a dynamical phase transition. Its properties and its importance for the understanding of the dynamics of local observables will be illustrated for quenches in the one-dimensional transverse-field Ising model.

[1] M. Heyl, A. Polkovnikov, S. Kehrein, arXiv: 1206.2505 (2012)

A_{1g}-phonon-induced electron structure dynamics of Fe-pnictides: enhanced spin density wave fluctuations

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We employ the five-orbital tight-binding model to study the A_{1g} phonon-induced electron dynamics of the Fe pnictides in the context of recent tr-ARPES experiments on $BaFe_2As_2$. By analyzing the experimental data [1] we deduce the amplitude of the tetrahedra angle oscillation due to A_{1g} phonon and the modified band structure topology. We also find that in order to account for the experimental data in the coherent regime the oscillations of the electronic structure should occur simultaneously with oscillations of the charge density on the iron site and we evaluate the amplitude of these oscillations from the five orbital model. Finally, we analyze the change in the magnetization as a function of the tetrahedral angle and find it is not symmetric around the mean value. This results in a higher value of the average magnetization within a cycle of the A_{1g} phonon compared to the magnetization for m_0. This suggests that coherent oscillation of the A_{1g} phonon mode may induce transient generation of the SDW state.

[1] L. Rettig, *Ultrafast Dynamics of Correlated Electrons*, Ph.D. Thesis, Free University of Berlin (2013)

Measurement of the unoccupied states in pump-probe experiments through the time-dependent momentum distribution

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The unoccupied states of complex materials are difficult to measure, yet play a key role in determining their emergent properties. We propose a novel technique that can measure the unoccupied states, time-resolved Compton scattering, which measures the time-dependent momentum distribution (TDMD). Using a non-equilibrium Keldysh formalism, we study the TDMD for electrons coupled to a lattice in a pump-probe setup. The non-equilibrium Keldysh formalism has been used successfully to study time-resolved ARPES (tr-ARPES) in correlated systems.[1,2] The electron-lattice interaction leads to temporal oscillations in the TDMD, and we find a direct relation between said oscillations and the underlying unoccupied states, suggesting that both can be measured by time-resolved Compton scattering. Alternatively, the TDMD can be measured by energy-integrated tr-ARPES.

In addition to its use as a direct measurement, the TDMD is a basic concept that is useful in understanding other complex pump-probe measurements, since it makes a direct connection to the well-known Boltzmann equation.

These results have been submitted for publication, and a preprint is available.[3]

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[2] B. Moritz, T.P. Devereaux, J.K. Freericks, Physical Review B 81, 165112 (2010)
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Nonequilibrium dynamics of the ohmic spin-boson model

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We study the nonequilibrium dynamics of the unbiased, ohmic spin-boson model close to the coherent-to-incoherent transition. In a first setup the system is prepared in a product state. Using complementary renormalization group methods we obtain numerical results for the spin expectation value on all time scales. They are supplemented by an analytical study for intermediate times. In the coherent regime the time evolution for those is characterized by the subtle interplay of damped oscillatory and purely exponential terms. Secondly, we investigate the dynamics when abruptly switching the coupling from a value in the incoherent regime to one in the coherent one. The incoherent dynamics before the quench heavily affects the one after it up to the extend that a critical coupling strength is required to observe nonmonotonic behavior. This exemplifies the importance of non-markovian memory.

Generation of incoherent phonons in a superconductor by ultrafast pump pulses

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We study the generation of incoherent phonons in a superconductor by ultrafast pump pulses. The nonequilibrium dynamics of the coupled Bogoliubov quasi-particle phonon system is analyzed by use of the density matrix formalism. Here the dynamics of the phonons is treated at a fully quantum kinetic level.

We investigate the influence of the incoherent phonons and quasi-particle phonon scattering processes on the coherent phonons. Those processes give rise to a finite lifetime of coherent phonons and lead to an exponential damping of coherent phonons oscillations.

Dielectric breakdown in spin polarized Mott insulator

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Nonlinear response of a Mott insulator to constant external electric field, corresponding to dielectric breakdown phenomenon, is studied within of a one-dimensional half-filled Hubbard model [1]. It is shown that in the limit of nearly spin polarized insulator (with one spin-↓ electron in a spin-↑ background) the decay rate of the ground state into excited holon-doublon pair can be evaluated numerically as well to high accuracy analytically. Results show exponential dependence of the decay rate on the fieldwith the threshold field having a particular scaling with the charge gap. Numerical results obtained with exact diagonalization on small systems indicate on the persistence of a similar mechanism for the breakdown for decreasing magnetization down to unpolarized system.

[1] Z. Lenarčič and P. Prelovšek, Phys. Rev. Lett. 108, 196401 (2012).

Extreme phonon softening and transient reversal of the Peierls-distortion in laser-excited Bismuth

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Femtosecond time-resolved X-ray diffraction can provide direct information about the dynamical changes of the atomic configuration in laser-excited materials. In this work coherent optical phonons were investigated in laser-excited Bismuth with time-resolved X-ray diffraction using ultrashort X-ray pulses from a laser-induced plasma. For low excitation fluences softening of the excited A_{1g} phonon mode was observed and the measured data are in good agreement with the earlier results [1, 2]. Extending our studies to high excitation fluences that have not been studied previously, our data reveal a complete softening of the A_{1g} mode. This gives clear experimental evidence that the Peierls-distortion, which defines the equilibrium structure of Bismuth, is transiently reversed and the material transformed into a state of higher symmetry.

[1] K. Sokolowski-Tinten et al., Nature **422**, 287 (2003)
[2] D. M. Fritz et al., Science **315**, 633 (2007).

Quasiparticle relaxation through the superconducting-like gap above T_c measured by multipulse femtosecond spectroscopy in $Bi_2Sr_2CaCu_2O_{8+d}$

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In conventional pump-probe experiments above T_c weak superconducting component of transient reflectivity signals cannot be distinguished from the strong pseudogap component. Novel three pulse technique [1] allows us to measure recovery of the superconducting state after superconducting-to-normal state laser induced transition. In the low excitation regime this kind of phase transition occurs without perturbing the pseudogap subsystem [2] thus allowing us to detect the recovery of weak superconducting component above Tc (determined by susceptibility measurements).

In the present work we investigated underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ 2212 with T_c =81 K and show appearance of the superconducting quasiparticle response up to 102 K. This temperature is 11 K higher than T_c of optimally doped samples, so the effect cannot be attributed to local inhomogeneities.

Superconducting fluctuations above T_c were previously observed in cuprates in ARPES measurements [3], diamagnetic effect [4], Nernst effect [5] and specific heat [6]. Our measurements represent a qualitative advance with respect to these measurements, as we do not use assumptions of PG behavior to separate the superconducting component from our signal. More important, we gain new information about the lifetime of the photoexcited quasiparticles in the fluctuating state and the recovery time of the state itself (i.e. the Ginzburg-Landau time).

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[2] Toda et al., Phys. Rev. B 84, 174516 (2011)
[3] Kondo et al. Nat.Phys. 7, 21–25 (2011)
[4] Li et al. Phys. Rev. B 81, 054510 (2010)
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[6] Tallon et al. preprint at http://arxiv.org/abs/0908.4428 (2009).

Optical and magnetooptical time-resolved study of spin dynamics in $EuFe_2(As_{1-x}P_x)_2$ pnictide superconductor

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We investigated temperature and magnetic field dependent photoexcited electron and spin relaxation in $EuFe_2(As_{0.7}P_{0.3})_2$ (EFAP) pnictide superconductor and parent nonsuperconductive $EuFe_2As_2$ (EFA) by means of optical pump-probe femtosecond spectroscopy. A remarkable change of the quasiparticle relaxation dynamics at the antiferromagnetic (AFM) spin density wave (SDW) transition temperature 200 K is observed in EFA, consistent with a bottleneck formation due to a charge gap opening.

In both samples we observe at low temperature an emergence of a slow anisotropic photoinduced relaxation component concurrent with Eu^{2+} spin ordering. The magnetic field dependence of the relaxation in the superconductive EFAP is different than in the nonsuperconductive EFA. In EFA we observe switching of the optical-transients anisotropy with increasing magnetic field attributed to a field-induced antiferromagnetic (AFM) to ferromagnetic (FM) phase transition. In the superconductive EFAP a large coherent magnon oscillation is observed at a similar metamagnetic transition. The oscillation is absent in the transient magneto-optical Kerr effect suggesting an interplay between the Eu^{2+} spin and charge degrees of freedom.

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Kinetic description of the thermalization dynamics of weakly interacting quantum systems

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After a sudden disruption, weakly interacting quantum systems first relax to a prethermalized state [1] that can be described by perturbation theory and a generalized Gibbs ensemble [2]. Using these properties of the prethermalized state we perturbatively derive a kinetic equation which becomes a quantum Boltzmann equation in the scaling limit of vanishing interaction [3]. Applying this to interaction quenches in the fermionic Hubbard model [4] we find that the momentum distribution relaxes to the thermal prediction of statistical mechanics. For not too large interaction, this two-stage scenario can thus provide a quantitative understanding of the time evolution leading from a pure initial state to the thermal state.

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ARPES studies of ironpnictide superconductors

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We will present a systematic study on the electronic structure and superconducting (SC) gaps in electron-doped $NaFe_{0.95}Co_{0.05}As$ superconductor using angle-resolved photoemission spectroscopy [1]. Holelike Fermi sheets are at the Brillouin zone center and electronlike Fermi sheets are at the zone corner, and are mainly contributed by *xz* and *yz* orbital characters. Our results reveal a Δ/K_B*T_c in the range of 1.8–2.1, suggesting weak-coupling superconductivity in these compounds. Gap closing above the transition temperature (T_c) shows the absence of pseudogaps. Gap evolution with temperature follows the BCS gap equation near the Γ, Z, and M high symmetry points. Furthermore, an almost isotropic superconductivity along the k_z direction in the momentum space is observed by varying the excitation energies. Alike in other doped ironpnictides we see an absence of nesting conditions between hole and electron pockets. We further show ARPES studies performed on entirely a different type of ironpnictides, $(CaFe_{1-x}Pt_xAs)_{10}Pt_nAs_8$ (10n8), in which the tetrahedral $FeAs_4$ layers sandwiched between the planar Pt_nAs_8 intermediary layers [2]. We will compare the electronic structure of 10n8 compounds with the known ironpnictides such as 1111, 122, and 111 [3].

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Light induced resistive switching to a hidden state in 1T-TaS_2

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Transition metal dichalcogenite TaS_2 is historically one of the first two-dimensional systems in which a charge density wave (CDW) was observed. With decreasing of temperature CDW follows two transitions from incommensurate CDW to near-commensurate and then to a commensurate CDW below 180K.

It is shown that at low temperature (below 100K) switching occurs from commensurate CDW to a metastable hidden state, caused by a single 50-fs laser pulse. This state is attributed to a textured CDW. The switching to photoinduced (p-TaS_2) state is reversible and the state can be "erased" by annealing or by laser pulses.

The switching is observed in electrical resistivity measurements: in the photoinduced state the DC resistance decreases after exposure, depending on energy density of the "writing" pulses (Fig. 1). Switching is also observed in the optical conductivity σ(ω) at 1.5 eV (800 nm), and most spectacularly is accompanied by changes in the collective mode spectrum measured by the coherent optical phonon spectroscopy.

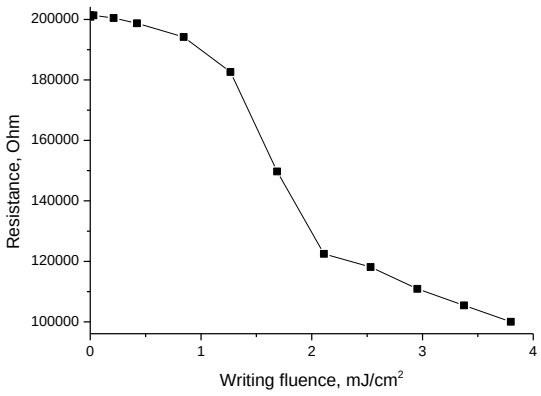

Figure 2. Dependence of the resistance on the fluence of "writing" optical pulse train.

Nonequilibrium dynamics of doped antiferromagnetic Mott insulators in two dimensions

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Out-of-equilibrium dynamics of 2D antiferromagnetic Mott insulators represents an exciting and widely unexplored field of both theoretical and experimental research. We study by means of numerical calculations how doped holes (charge carriers) described within the t-J model and t-J-Holstein model behave under highly nonequilibrium conditions. In particular, we investigate how the accumulated energy (e.g., in the steady state if the electric field is constant, or during the relaxation process if a laser excitation is applied) is transferred from charge carriers to quantum spin and phonon degrees of freedom contained within the model.
I will first present two examples revealing peculiarities of nonequilibrium dynamics in two dimensions [1,2]. The first example concerns the steady state of a single hole driven by a constant electric field, where at large electric fields the propagation of hole in direction transverse to the field represents an efficient channel to emit its excess energy [1]. In the second example, I will show that the decay of a bound state of two holes on the square lattice is governed by the predominant motion in the direction transverse to the electric field, leading to much shorter decay times than on a quasi one-dimensional ladder system [2].
Then I will address the steady state properties of a driven hole within the t-J-Holstein model, where the energy gained by the propagation along the field can flow to both spin and phonon subsystem [3]. Investigation of such multi-component system under nonequilibrium conditions is motivated by recent pump-probe experiments, and addresses a highly nontrivial question about the main relaxation mechanism of two-dimensional strongly correlated materials. Our results indicate that for values of model parameters as relevant for materials like cuprates, the gained energy in the steady state flows predominantly to the spin subsystem.
Finally, I will discuss relaxation dynamics of doped systems after a short laser excitation, and focus on relaxation mechanisms emerging from charge-spin and charge-phonon coupling [4].

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Ultrafast spin dynamics in epitaxial Co/Cu(001) analyzed by femtosecond time-resolved linear and non-linear magneto optics

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In order to investigate the microscopic processes in laser-induced demagnetisation, we performed pump probe measurements at Co/Cu(001) films at thicknesses 5 ML< d < 30 ML. We used simultaneously time resolved magneto-optical Kerr effect (MOKE) and magneto induced second harmonic generation (MSHG) in a transversal geometry. The transient nonlinear MSHG signal is essentially independent on thickness, whereas the linear MOKE signal shows an increasing pump induced demagnetisation ΔM and an increase in the demagnetization time for larger d. Since MSHG is generated at the film's interfaces and MOKE probes the film as a whole we conclude from the observed thickness dependence that different mechanisms contribute to the laser- induced change of the magnetization. At smallest d transport contributions might represent the dominant channel [1,2], while for larger d also slower, local processes like angular momentum transfer to phonons [3] become relevant.

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Short-time Dynamics in Strongly Correlated Systems and Novel Superconductors - Timetable

Time\Day	Monday	Time →	Tuesday	Time →	Wednesday	Time →	Thursday
08:45 - 09:00	Arrival & Opening						
09:00 - 09:40	M. Wolf	09:00 - 09:40	J. Freericks	09:00 - 09:40	Th. Elsässer	09:00 - 09:40	D. Mihailovic
09:40 - 10:20	P. Echenique	09:40 - 10:20	D. Manske	09:40 - 10:20	A. Lichtenstein	09:40 - 10:20	H. Kroha
10:20 - 11:00	Coffee break	10:20 - 11:00	Coffee break	10:20 - 11:00	Coffee break	10:20 - 11:00	Coffee break
11:00 - 11:40	M. Bauer	11:00 - 11:40	T.P. Devereaux	11:00 - 11:25	J. Mentink	11:00 - 11:40	M. Kollar
11:40 - 12:05	V. Meden	11:40 - 12:05	Th. Fauster	11:25 - 12:05	A. Alvermann	11:40 - 12:05	M. Croitoru
12:05 - 12:30	M. Schiro	12:05 - 12:30	M. Hengsberger	12:05 - 12:45	M. Eckstein	12:05 - 12:30	J. Berakdar
12:30 - 14:00	Lunch	12:30 - 14:00	Lunch	12:45 - 14:20	Lunch	12:30 - 14:00	Lunch
14:00 - 14:40	M. Fiebig	14:00 - 14:25	P. Prelovsek	14:20 - 15:00	Travel to excursion	14:00 - 14:40	J. Demsar
14:40 - 15:05	W. Huebner	14:25 - 14:50	R. Schützhold	15:00 - 18:00	Deutsches Bergbaumuseum	14:40 - 15:20	C. Gianetti
15:05 - 15:30	I. Radu	14:50 - 15:30	A. Cavalleri			15:20 - 16:00	Coffee break
15:30 - 16:10	Coffee break	15:30 - 16:10	Coffee break			16:00 - 16:40	A. Lanzara
16:10 - 16:35	F. Anders	16:10 - 19:00	Poster session			16:40 - 17:20	A. Leitenstorfer
16:35 - 17:00	D. Schuricht					17:20 - 17:30	Closure
17:00 - 17:40	C. Kollath						
17:40 - 18:20	S. Kehrein						
18:20 - 19:30	Dinner			18:00 - 18:30	Walk to		
19:30 - 19:45	D. Eberle			18:30 - 22:00	Banquet		
19:45 - 20:30	J. Fink						