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Giuliano Orso (Université Paris Diderot-Paris 7 & CNRS)

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Andrea Perucchi (Elettra, Trieste)

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Bilal Tanatar (Bilkent University)

Interaction and Disorder Effects Across BCS-BEC Crossover in Three- and Two-Dimensional Fermi Gases

Erik Van Heumen (University of Amsterdam)

Boosting the critical temperature in Co-doped Ba122: a spectroscopic view

Incidence of electronic correlations on the Superconductivity near the Mott transition of alkali fullerides

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Most investigations on correlated electron systems deal with the interplay of magnetism and superconductivity (SC). Indeed in many families of compounds in which electronic correlations (EC) are of importance, the phase diagrams exhibit magnetic phases proximate with a SC phase. It is often thought that the ECs are at the origin of the superconducting pairing.

Here we address a specific case of SC in the A_3C_{60} compounds [1], where A is an alkali metal. Former extensive investigations mainly by NMR techniques, have led one to consider that a BCS electron-phonon mechanism prevails[2], suggesting a negligible incidence of ECs. However further detailed studies of A_nC_{60} compounds with $n = 1, 2, 4$ [3] , [4] gave evidences that their electronic properties cannot be explained by a simple band filling of the C_{60} molecular level. This could only be ascribed to the influence of ECs and of Jahn-Teller Distortions of the C_{60} ball, which favour evenly charged C_{60} molecules [3].

The discovery of two Cs_3C_{60} isomeric compounds Cs_3C_{60} which exhibit a transition with pressure from a Mott insulator to a SC state clearly emphasize the importance of ECs [5], [6]. Using pressure (p) as a single control parameter of the C_{60} balls lattice spacing, one can now study the evolution of the SC properties when the corelations are increased towards the critical pressure p_c of the Mott transition.

We have used ^{13}C and ^{133}Cs NMR data taken on the $A15$-Cs_3C_{60} cubic phase, just above $p_c = 5.0(3)$ kbar, where the SC T_c displays a dome shape with decreasing cell volume [7]. From the T dependence below T_c of the nuclear spin lattice relaxation rate $(T_1)^{-1}$ we determine the electronic excitations in the SC state, that is 2Δ, the gap value. The latter is found to be largely enhanced with respect to the BCS value established in the case of dense A_3C_{60} compounds. It even increases slightly with decreasing p towards p_c, where T_c decreases on the SC dome, so that $2\Delta/k_BT_c$ increases regularly upon approaching the Mott transition. These results bring clear evidence that the increasing correlations near the Mott transition are not significantly detrimental to SC. They rather suggest that repulsive electron interactions might even reinforce electron-phonon SC, being then partly responsible for the large T_c values, as proposed by theoretical models taking the ECs as a key ingredient [8].

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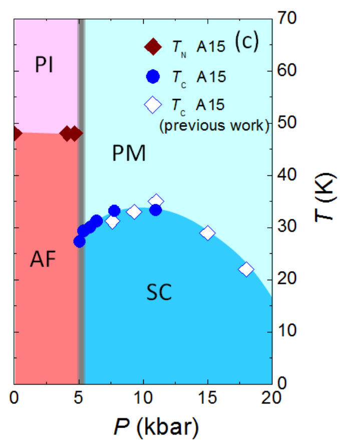

First-principles study of the Mott transition and superconductivity in A_3C_{60}

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Doped fullerides A_3C_{60} (A=alkali metal), which turn superconducting with a maximum transition temperature (T_c) of $\sim$ 40K, have attracted increasing attention. As for the pairing mechanism, the validity of the standard Migdal-Eliashberg theory has been questioned[1]. In *ab initio* calculation based on superconducting density functional theory[2], which works successfully for conventional superconductors, T_cs are estimated less than half of the experimental value[3].

In 2002, the emergence of phonon-driven superconductivity close to the Mott transition [strongly correlated superconductivity (SCS)] was proposed[4]. The key of this proposal is the presence of a weak phonon-driven attraction in the form of an inverted Hund's rule coupling, which is not renormalized by the strong short-range repulsion. However, the interacting parameters in the Hamiltonian are yet to be evaluated from first principles.

Recently, we developed an *ab initio* downfolding scheme, which we call "constrained density-functional perturbation theory" [5], to derive the electron-phonon coupled effective Hamiltonian. We applied this method to C_{60} superconductors, and found that the magnitude of the phonon-mediated exchange interaction $J_{\rm ph}$ is $\sim$ 0.05 eV. By the constrained random phase approximation[6], we also estimated the electron-electron interactions such as Hubbard U, distant Coulomb repulsions V, and the Hund's coupling $J_{\rm H}$[7]. We find that $J_{\rm H}$ is $\sim$ 0.035 eV ($< J_{\rm ph}$), which suggests that SCS is indeed realized in doped C_{60} superconductors.

By means of extended dynamical mean field theory[8], we then solved the resulting effective low energy model, where we consider the anomalous Green's function. We calculated T_c as a function of the volume of the unit cell. We also determined the phase boundary between the metallic phase and the Mott insulating phase. We show that the obtained phase diagram agrees well with the experiment quantitatively[9].

This work has been done in collaboration with Y. Nomura, R. Akashi (University of Tokyo), S. Sakai (RIKEN), K. Nakamura (Kyushu Institute of Technology) and M. Capone (International School for Advanced Studies, Italy)

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The Superfluid Mass Density and the Landau Criterion for Superfluidity

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This talk will focus on the theory of the superfluid mass density in superfluids. Topics to be discussed include: the microscopic theory of the superfluid mass density; why the Landau criterion for superfluidity is neither necessary nor sufficient; and the superfluid mass density in ultracold bosonic and fermionic atomic systems.

Magnetism, self-doping and incipient Mott Physics in the Fe-intercalated Fe-selenide LiFeO2FeSe

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A series of recent experiments has shown that the magnetic order and superconducting critical temperatures of Fe selenides can be tuned by intercalation with foreign atoms, molecular layers, or epitaxial growth. In this work, [1] we employ a combination of density functional theory (DFT) and dynamical mean field theory (DMFT), to show the electronic structure of a very special intercalated selenide, which was reported to be superconducting with a critical temperature (T_c) of 43 K in the fall of 2013. [2] In this compound, with chemical formula LiFeO2FeSe, the FeSe layers alternate with LiFeO2 layers. Together with Sr2VO3FeAs, [3] this is to date the only example of iron-based superconductor with a magnetic buffer layer. What makes this compound even more special is that the magnetic atom in the buffer layer - Fe(Li) - is also an iron atom, but in a nominal d5 configuration, while the iron in the chalchogenide planes - Fe(Se) - is in the usual d6 configuration of Fe-based superconductors.

At a DFT level, both layers contribute states to the Fermi surface, which is therefore more complicated than in usual FeSe superconductors. The ground state is an antiferromagnetic metal, in which Fe(Li) and Fe(Se) have sizable magnetic moments - 3.6 and 2.6 mB respectively ? with a strong mutual antiferromagnetic coupling. Including dynamical correlations in DMFT results in a very different behavior for the two Fe atoms: Fe(Se)-derived bands retain a quasi-particle character, with a mass renormalization comparable to that of pure FeSe [4]; on the other hand, since Fe(Li) is close to an orbital-selective Mott transition regime, [5] the relative bands have a strongly incoherent character and are almost completely removed from the Fermi level.

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A quantum point contact for ultra cold Fermions

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We report on the observation of quantized conductance in the transport of a neutral Fermi gas of atoms [1]. We employ ultra-high resolution lithography to shape light potentials that realize either a quantum point contact or a quantum wire for atoms. These constrictions are imprinted on a quasi two-dimensional ballistic channel connecting two adjustable reservoirs of quantum degenerate fermionic lithium atoms. By tuning either a gate potential or the transverse confinements of the constrictions, we observe distinct plateaus in the conductance for matter. The conductance in the first plateau is found to be equal to 1/ h, the universal conductance quantum. For low gate potentials we find good agreement between the experimental data and the Landauer formula with all parameters determined a priori. By tuning interactions using a Feshbach resonance, the same experimental configuration realises a superfluid point contact with a non-linear current-bias relation.

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Orbital-driven nematicity and superconductivity in FeSe: NMR study

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Since the discovery of the iron based superconductors, the origin of the nematic tetragonal-to-orthorhombic transition has been hotly debated. Since in most iron pnictide families, the nematic transition occurs very close to the antiferromagnetic instability, it has been argued that the nematicity stems from the magnetic spin fluctuations, coupled to the lattice degrees of freedom. The iron selenide FeSe is different in that the structural transition occurs at Ts ~ 90 K without any sign of antiferromagnetism, and it is therefore tempting to conclude that an alternative scenario for nematicity, based on orbital (rather than spin) degrees of freedom, takes place. To establish whether this is indeed the case, we have conducted extensive nuclear magnetic resonance (NMR) measurements on FeSe. Below the nematic transition temperature Ts, we observe a clear splitting of the Se NMR line, which we show to be of electronic origin. Moreover, by measuring the spin-lattice relaxation rate and Knight shift, we establish unequivocally that this line splitting is driven by orbital nematic order. We furthermore establish a connection between orbital nematicity and superconductivity, showing that the two order parameters compete with each other. Intriguingly, this may provide an explanation for the very high superconducting transition temperature reported in the single-layer FeSe.

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Real-time oscillations of the superconducting condensate in a high-Tc superconductor

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Here, the observation of the coherent oscillations of the Cooper pairs condensate in a superconductor is presented [1]. Superconductvity is set out of equilibrium by populating selected charge fluctuations via the electronic impulsive stimulated Raman scattering mechanism. The consequent effects on the materials electronic structure are detected via ultrafast optical spectroscopy, revealing oscillations that resonate at particular energies. Unraveling the complex interplay between electronic and lattice degrees of freedom is one of the keys towards understanding the unconventional pairing mechanism in cuprates. In these expriments, we probe an optimally doped La2-xSrxCuO4 (x=0.15) single crystals. Our data reveal the temporal evolution of the pair-breaking excitations as well as the coherent oscillation of the out-of plane motion of lanthanum ions. In these experiments, the real-time observation of quantum states of matter both in amplitude and phase gives information on the coupling between high energy electronic transitions like stripes bands and charge transfers, and low-energy excitations. These coherent oscillations, detected by the transient optical properties for the first time, reveal strong resonance effects between the oscillating condensate and particular atomic motions and charge fluctuations. The resonance of these oscillations with the charge transfer energy scale suggest a contribution of high energy states to the pairing mechanism in high Tc cuprates.

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Current patterns and optical conductivity in disordered superconductors

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We study the disordered attractive Hubbard model by solving the BdG equations on two-dimensional finite clusters at zero temperature. By coupling the sample to an external field we find that the current density is strongly inhomogeneous, with almost one-dimensional patterns, in rough agreement with Ioffe and Mezard recent proposal of a low temperature glassy phase in disorder superconductors.

The optical conductivity besides the quasi-particle contribution shows an intra-gap absorption due to collective modes. These excitations are related to the phase of the superconducting (SC) order parameter and for clean systems they are optically inactive. Here we show that for strongly disordered superconductors the phase modes acquire a dipole moment and appear as a subgap spectral feature in the optical conductivity. In the strongly disordered regime, where the system displays an effective granularity of the SC properties, the optically active dipoles are linked to the isolated SC islands, offering a new perspective for microwave measurements and optical devices.

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Composite charge order in cuprate superconductors

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Ianalyze charge order in hole-doped cuprates [1, 2]. I argue that magnetically-mediated interaction, which is known to give rise to d-wave superconductivity, also gives rise to charge-density-wave instabilities with momenta $Q_x = (Q, 0)$ and $Q_y = (0, Q)$, as seen in the experiments. I show that the emerging charge order with Q_x/Q_y is of stripe type and that a stripe charge order parameter by itself has two components: one is incommensurate density variation, another is incommensurate current. Both components are non-zero in the CDW-ordered state, with the relative phase +- $\pi/2$. Such an order breaks time reversal symmetry. I further show that, before a true incommensurate CDW order sets in, the system develops a pre-emptive composite order which breaks lattice rotational symmetry and time-reversal symmetry but preserves a translational U(1) symmetry. I discuss the interplay between our CDW order and superconductivity and the spin-fluctuation scenario for the pseudogap phase.

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Creation and characterization of defects in a Bose-Einstein condensate of sodium atoms

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Experimental observations and numerical simulations of defects created in a Bose-Einstein condensate after a rapid quench across the BEC transition [1, 2] are presented. When a system crosses a second-order phase transition on a finite timescale, spontaneous symmetry breaking can cause the development of domains with independent order parameters, which then grow and approach each other creating boundary defects. This is known as the Kibble-Zurek mechanism (KZM). Here we report on the observation of phase defects of the order parameter, spontaneously created in an elongated BEC of sodium atoms. We show that the number of defects in the final condensate grows according to a power law as a function of the rate at which the transition is crossed, consistently with the expectations of the KZM. The defects are imaged after a long time-of-flight in free expansion, when the defect structure is clearly visible both in terms of size and optical density. A triaxial absorption imaging system allows us to identify the defects as topological excitations known as solitonic vortices [3, 4]. These excitations have a very long lifetime and, after the expansion, they exhibit a peculiar twisted planar density depletion around a vortex line. In order to prove the quantized vorticity of the observed defects, we also implement a matter wave interferometer in which the presence of vorticity is revealed by dislocations in the fringe pattern. Both the twist in the density distribution seen in absorption images and the shape of the fringe discolations in interferometric measurements allow us to determine the sign of the quantized circulation. Numerical simulations based on the Gross-Pitaevskii equation are used to support the physical interpretation of the experimental results and to test the dependence of the solitonic vortex structure on the key parameters of the system, such as the geometry and the interaction. Our observations of solitonic vortices in a dilute BEC complement those of Refs. [5, 6] in Fermi superfluids in the BCS-BEC crossover, and may serve as a basis for a systematic investigation of topological defects and solitons in quantum gases with variable geometry, from highly elongated quasi-1D to strongly oblate quasi-2D shapes.

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Interplay of d-symmetry Cooper pairs and d-symmetry density waves in underdoped cuprates

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A central issue of cuprate superconductivity research is to understand the nature of *pseudogap* phase and its relationship to the *d*-wave superconductivity. Using our recently developed technique of sub-lattice phase-resolved electronic structure visualization[1] within each CuO_2 unit-cell, we discovered that the cuprate pseudogap state is a d-symmetry form factor density wave [2]. Although long predicted, such an unconventional density-wave state has not previously been observed in any condensed matter system. Next, our simultaneous visualizations of both real-space and momentum-space electronic structure across the cuprate phase diagram revealed that the famous transition of momentum-space topology from "Fermi arc" to conventional Fermi surface occurs simultaneously with the disappearance of the *d*-form factor density wave[3]. Taken together these results provide the first atomic scale understanding of the interplay between the d-symmetry density waves and d-symmetry Cooper pairing in underdoped cuprates.

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Reverse-engineering electronic correlations in Iron superconductors

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I will discuss the strength of electronic correlations in the normal phase of Fe superconductors.

It will be shown that the agreement between a wealth of experiments and DFT+DMFT or similar approaches supports a scenario in which strongly-correlated and weakly-correlated electrons coexist in the conduction bands of these materials.

I will then reverse-engineer the realistic calculations and justify this scenario in terms of simpler behaviors easily interpreted through model results[1].

All pieces come together to show that Hund's coupling, besides being responsible for the electronic correlations even in absence of a strong Coulomb repulsion (and indeed being also essential to explain the magnetically ordered phases found in the phase diagrams) is also the origin of a subtle emergent behavior: orbital decoupling. Indeed Hund's exchange decouples the charge excitations in the different Iron orbitals involved in the conduction bands thus causing an independent tuning of the degree of electronic correlation in each one of them. The latter becomes sensitive almost only to the offset of the orbital population from half-filling, where a Mott insulating states is invariably realized at these interaction strengths. Depending on the difference in orbital population a different "Mottness" [2] affects each orbital, and thus reflects in the conduction bands and in the Fermi surfaces depending on the orbital content. This selective Mottness is put in perspective with the analogous differentiation of electronic correlation in k space found in the underdoped cuprates (see e.g. [3]) and a common phase diagram is sketched.

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Superconductivity from repulsion in LiFeAs: Novel s-wave symmetry and potential time-reversal symmetry breaking

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In my talk I will review the multiband aspects of superconductivity arising from repulsive interaction with weak spin fluctuations. Most importantly, I will analyze the structure of the pairing interaction and superconducting gaps for LiFeAs, which electronic structure and superconducting gaps are well studeid by ARPES. We use the ten-orbital tight-binding model, derived from ab-initio LDA calculations with hopping parameters extracted from the fit to ARPES experiments. We find that the pairing interaction almost decouples between two subsets, one consists of the outer hole pocket and two electron pockets, which are quasi-2D and are made largely out of dxy orbital, and the other consists of the two inner hole pockets, which are quasi-3D and are made mostly out of dxz and dyz orbitals. Furthermore, the bare inter-pocket and intra-pocket interactions within each subset are nearly equal. In this situation, small changes in the intra-pocket and inter-pocket interactions due to renormalizations by high-energy fermions give rise to a variety of different gap structures. Different s-wave gap configurations emerge depending on whether the renormalized interactions increase attraction within each subset or increase the coupling between particular components of the two subsets. We argue that the state with opposite sign of the gaps on the two inner hole pockets has the best overlap with ARPES data.

Fluctuating Charge Density Waves in a Cuprate Superconductor

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Cuprate materials hosting high-temperature superconductivity (HTS) also exhibit various forms of charge and spin ordering whose significance is not fully understood. So far, static charge-density waves (CDWs) have been detected by diffraction probes only at particular doping levels or in an applied external field. However, dynamic CDWs may also be present more broadly and their detection, characterization and relationship with HTS remain open problems. Here we present a method based on ultrafast spectroscopy to detect the presence and measure the lifetimes of CDW fluctuations in cuprates [1]. In an underdoped $La_{1.9}Sr_{0.1}CuO_4$ film ($T_c = 26$ K), we observe collective excitations of CDW that persist up to 100 K. This dynamic CDW fluctuates with a characteristic lifetime of 2 ps at $T = 5$ K that decreases to 0.5 ps at $T = 100$ K. In contrast, in an optimally doped $La_{1.84}Sr_{0.16}CuO_4$ film ($T_c = 38.5$ K), we detect no signatures of fluctuating CDWs at any temperature, favouring the competition scenario. This work forges a path for studying fluctuating order parameters in various superconductors and other materials.

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Snapshots of the retarded interaction of charge charriers with ultrafast fluctuations in cuprates

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One of the pivotal questions in the physics of high-temperature superconductors is whether the low-energy dynamics of the charge carriers is mediated by bosons with a characteristic timescale. This issue has remained elusive since electronic correlations are expected to dramatically speed up the electron-boson scattering processes, confining them to the very femtosecond timescale that is hard to access even with state-of-the-art ultrafast techniques. Here we simultaneously push the time resolution and the frequency range of transient reflectivity measurements up to an unprecedented level that enables us to directly observe the ∼16 fs build-up of the effective electron-boson interaction in hole-doped copper oxides. This extremely fast timescale, together with the outcome of calculations for the t-J model and the repulsive Hubbard model, indicates that short-range antiferromagnetic fluctuations are the bosons that likely mediate the retarded electron interactions in copper oxides close to optimal doping, where the largest critical temperature is reached.

Spectroscopic aspects and pairing glue of superconductivity in the 2D Hubbard model

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We explore spectroscopic and energetic aspects of the d-wave superconducting state found in the intermediate correlation regime of the two-dimensional Hubbard model. Recently developed continuous-time quantum Monte Carlo and quantum cluster methods have enabled the explicit construction of this superconducting state on the same footing as the normal state metal, the pseudogap, and the Mott state. We focus on the interplay of these states and the evolution of the c-axis and Raman response functions and analyze the pairing glue.

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Quenched superconductors across BCS-BEC crossover: topological states out of equilibrium

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We examine the behavior of superconductors whose interactions were suddenly quenched (changed in magnitude), a process which is easy to implement experimentally in the context of cold atoms, but which is also not entirely out of reach in the solid state context. Queches which leave the interactions weak were thoroughly studied in the past, including by some of us; we extend this analysis to quenches where initial and final interactions can be arbitrarily strong. We map out the "phase diagram" where each quench is matched with the long time behavior of the superconductor after the quench. Particularly interesting are quenches in the two-dimensional p-wave atomic condensates, as such superfluids can be topological in equilibrium. At the same time while p-wave atomic condensates are hard to bring to equilibrium in experiment because of the condensate decay their quenches are probably within the reach of experiment. We demonstrate that such superconductors reach steady states soon after their quenches which for some quenches retain the topological characteristics of their equilibrium counterparts.

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Superfluid and Transport Properties of Disordered Bose Gases in Two Dimensions

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We discuss the normal to superfluid transition of two-dimensional Bosons under the influence of a correlated disorder potential in parameter regimes directly relevant to experiments [1]. Using path-integral Monte Carlo calculations we establish the phase diagram for homogeneous systems. We further calculate the conductivity and characterize the insulating behavior at large disorder strength. Our calculation indicates that the conductance always exhibits a thermally activated behavior vanishing only at zero temperature [2].

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Two-dimensional Fermi gases

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Systems of interacting Fermions are ubiquitous in nature. They exhibit fascinating phenomena like superconductivity, quantum magnetism, superfluidity of 3He, and the anomalous rotation of neutron stars. Ultracold atomic Fermi gases allow for a particularly clean experimental realization of these quantum many-body systems and for addressing long-standing open questions. In this talk, we focus on situations in which the motion of particles is confined to two-dimensional layers. Such low-dimensional, interacting many-body systems bear subtle effects, which are not encountered in three dimensions. We will review our recent experiments regarding quasiparticle spectroscopy, spin diffusion measurements and in-situ observation of Mott-insulating domains.

Correlated Normal States and their Emergent Superconductivity

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Recent advances in electronic structure are finally begining to enable the understanding of different types of correlations and how they impact the resulting superconductivity starting from first principles. We will give an overview of recent insights on this problem, with examples drawn from interesting classes of materials including BaKBiO3 and LiFeAs. We will conclude with some perspectives on the challenge of assisting in the design of new materials.

Superconductivity and quantum phase transitions at oxide interfaces

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At the interface between insulating oxides such as SrTiO3/LaAlO3 or LaTiO3/SrTiO3, a superconducting two-dimensional electron gas (2DEG) has been discovered [1, 2, 3], whose carrier density can be tuned by applying a gate voltage. The unique possibility of modulating the superfluid density easily and continuously opens new perspectives to tackle fundamental issues in condensed matter physics, such as the Superconductor to Insulator Quantum Phase Transition (QPT) in a two-dimensional system. Using two different external parameters, the magnetic field and the electric field, we explored the phase diagram of the 2DEG. As proposed theoretically [4], we point out that the system can be described as a disordered array of coupled superconducting puddles. Depending on the conductance, the observed critical behaviour is single (corresponding to the long-range phase coherence in the whole array) or double (one at intermediate distances belonging to the (2+1)D clean XY universality class related to local phase coherence, the other one to the array of puddles) [5]. Moreover, by retrieving the coherence-length critical exponent ν, we show that the quantum critical behaviour can be clean or dirty according to the Harris criterion, depending on whether the phase-coherence length is smaller or larger than the size of the puddles. Finally, the electric-field driven QPT reveals an anomalous critical behavior. It can be understood if we assume that the dynamics in the Cooper pair channel is dominated by (nearly critical dynamical) density fluctuations in the low doping regime. This shades a new light on unexplained critical exponents found in the literature.

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Disordered bosonic systems

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I will report on experiments with ultracold quantum gases addressing the problem of disordered, interacting bosons close to T=0. A subtle interplay of kinetic, interaction and disorder energies determines whether a quantum system shows insulating, metallic or superfluid properties. One the one side, we are studying one-dimensional systems, where the competition between disorder and a strong repulsive interaction drives a continuous crossover between an Anderson insulator, a finite-T Bose glass, and a superfluid-like phase. On the other side, we are investigating how the Anderson localization problem in three dimensions is affected by a weak interaction. The large control of our ultracold atomic systems allows to perform unprecedented measurements of critical quantities that can be compared to advanced theoretical results.

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Spin-orbit coupling in an ultracold gas of Dysprosium: prospects towards topological superfluidity

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The Dysprosium atom exhibits a complex structure of electronic levels, with several narrow optical transitions. This should allow one to manipulate the atom internal degree of freedom using lasers in a new regime for which the spontaneous emission rate is negligible. I will discuss a particular laser coupling scheme which allows one to create an artificial spin-orbit coupling in a gas of fermionic Dy atoms. In the regime of strong interactions between atoms, one then expects the formation of a topological superfluid phase. The topological character of this phase is associated with the presence of robust edge states described as Majorana fermions, which are one of the simplest examples of quasi-particles with non-abelian quantum statistics. I will present several measurement schemes in order to probe the peculiar properties of this system.

Hetero-pairing and pseudogap phenomena in the BCS-BEC crossover regime of an ultracold Fermi gas with mass imbalance

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We theoretically discuss strong-coupling properties of an ultracold Fermi gas in the case when Cooper pairs are formed between different species with different masses ($m_{\rm L} < m_{\rm H}$). Including strong pairing fluctuations within a self-consistent T-matrix approximation, we self-consistently determine the superfluid phase transition temperature $T_{\rm c}$ for arbitrary ratio $m_{\rm L}/m_{\rm H}$ of mass imbalance, over the entire BCS-BEC crossover region[1,2]. In particular, we find that a ^{6}Li-^{40}K Fermi gas mixture ($m_{\rm L}/m_{\rm H} = 0.15 \ll 1$), which is a strong candidate for the mass-imbalanced Fermi gas superfluid, always has a finite $T_{\rm c}$ in the whole BCS-BEC crossover region. In the crossover region, we also show that the so-called pseudogap phenomenon associated with strong pairing fluctuations occurs, as in the case of ordinary mass-balanced Fermi gas ($m_{\rm L}/m_{\rm H} = 1$). However, in contrast to the mass-balanced case, detailed pseudogap structures are very different between the light mass component and heavy mass component, although both the components equally contribute to pairing fluctuations. In the highly mass-imbalance regime ($m_{\rm L}/m_{\rm H} \ll 1$), one finds that, while a clear pseudogap is seen in the density of states in the light mass component, such a dip structure is absent in the heavy mass component. Since hetero-Cooper pairs have recently been discussed in various fields, not only in cold Fermi gas physics, but also an exciton (polariton) condensate in semiconductor physics, as well as a color superconductor in particle physics, our results would contribute to the further understanding of these exotic Fermi superfluids.

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Towards dipolar quantum many-body physics with ultracold polar molecules

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The long range dipolar interaction between polar molecules is expected to pave the way to the study of intriguing phenomena such as quantum magnetism, supersolids and novel anisotropic superfluids. In this talk, I will review recent experimental progress in the preparation, manipulation and control of polar molecules. In particular, I will discuss recent experiments on collisional properties of polar molecules in the quantum regime. This includes chemical reactions and their control via quantum statistical properties, dipolar interactions and confinement in reduced dimensions [1, 2, 3, 4, 5]. Furthermore, I will present experimental progress towards the preparation of ultracold ground state NaK molecules with a large dipole moment of about 2,7 Debye [6].

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Universal properties of Bose-Fermi mixtures with a pairing interaction

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I will present a many-body diagrammatic formalism that is able to describe the condensed phase of a Bose-Fermi mixture in the presence of a contact pairing interaction between bosons and fermions, from weak to strong boson-fermion couplings. This approach will be validated by comparing it with previous [1] and new dedicated fixed-node diffusion Monte Carlo calculations. By using both methods, a universal behavior of the condensate fraction and bosonic momentum distribution with respect to the boson concentration $n_{\mathrm{B}}/n_{\mathrm{F}}$ will be unveiled, which extends from unitary concentration down to the limit of vanishing boson density. This universality connects some important properties of a Bose-Fermi mixture with corresponding properties of the polaron problem, which much attention has received in the context of strongly-interacting polarized Fermi gases. Finally, I will discuss an interesting effect occurring in the molecular limit of the boson-fermion coupling, where the condensation is completely suppressed [2]. This phenomenon is an indirect effect on the bosons of the Pauli exclusion principle acting on the fermions, and is the counterpart in a Bose-Fermi mixture of the so called “Sarma phase” discussed for polarized Fermi gases.

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BCS regime of the two-dimensional fermionic Hubbard model: ground-state phase diagram

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A significant part of the phase diagram of the two-dimensional fermionic Hubbard model—at least for moderate interactions and fillings ($U < 4$, $n < 0.7$)—is controlled by Fermi liquid physics with the microscopic interaction renormalized into weak BCS-type effective coupling. We access this regime in a controlled way by a combination of bold-line diagrammatic Monte Carlo with a peculiar ladder-diagram summation trick and semi-analytic treatment of the weak instability in the Cooper channel. We obtain the corresponding ground-state phase diagram in the (n, U) plane, describing the competition between the $p-$ and $d-$wave superfluid states. We also claim the values of the dimensionless BCS coupling constants—controlling the superfluid T_c—at the phase boundaries, which prove to be very small up to $U = 4, n = 0.6$.

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Second sound and the superfluid fraction in a resonantly interacting Fermi gas

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‘Second sound’ is a striking manifestation of the two-component nature of a superfluid, well known in context with liquid helium II. This form of sound, which only exists below the critical temperature, corresponds to an entropy wave, where the superfluid and the non-superfluid components oscillate in opposite phase. This is different from ordinary sound (‘first sound’), where the two components oscillate in phase. In this talk, I would report on the first observation of second sound in an atomic Fermi gas. Our results can be interpreted in terms of Landau’s famous two-fluid theory, and the measured second-sound speeds allow us to extract the temperature dependence of the superfluid fraction, which in strongly interacting quantum gases has been an inaccessible quantity so far.

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Cascade of Solitary Waves in a Fermionic Superfluid

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Topological excitations are found throughout nature, in proteins and DNA, as dislocations in crystals, as vortices and solitons in superfluids and superconductors, and generally in the wake of symmetry-breaking phase transitions. In fermionic systems, topological defects provide bound states for fermions that often play a crucial role for the system's transport properties. Famous examples are Andreev bound states inside vortex cores, fractionally charged solitons in relativistic quantum field theory, and the spinless charged solitons responsible for the high conductivity of polymers. Strongly interacting fermionic superfluids of ultracold atoms represent a fascinating new host material for the study of solitary waves it is a system for which we do not yet know the precise form of the wave equation governing these excitations. We have created solitons in a strongly interacting fermionic superfluid by imprinting a phase step into the superfluid wavefunction [1, 2], and directly observe the decay cascade from solitons to vortex rings and finally to single solitonic vortices. The remnant vortices are seen to precess for long times in the superfluid. The long period and the correspondingly large ratio of the inertial to the bare mass of the vortex are in good agreement with estimates based on superfluid hydrodynamics that we derive from the known equation of state in the BEC-BCS crossover. In future work we may be able to directly observe and control Andreev bound states superpositions of particles and holes trapped inside solitary waves.

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Ultra-cold atoms in sub-wavelength potentials.

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In this talk I will present a new ongoing project that aims at manipulating ultra cold atoms in nano-structured periodic optical potentials. Cold atoms in optical lattices have proven to be excellent candidates to simulates both the Bose and Fermi Hubbard models and brought to the forefront the topics of quantum simulators [1] that are now extensively studied. The ability to simulate with cold atoms the electronic conduction of graphene [2] or the properties of two dimensional electron gaz is an exciting perspectives. In this context, we are developing a new, original and challenging hybrid quantum system made of cold fermionic atoms and surface plasmons that will allow to manipulate ultra-cold atoms in sub-wavelength lattice potentials [3]. In this presentation, I will emphasize on the novelty and perspectives of our work.

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Downfolding electron-phonon Hamiltonians from ab-initio calculations: application to K_3 picene

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In this work[1], we propose an electron-phonon parameterization which reproduces the geometry and harmonic frequencies of a real system, by taking structural parameters either from experiment or density functional theory. With respect to standard electron-phonon models, it adds a "double-counting" correction, which takes into account the lattice deformation as the system is dressed by low-energy electron-phonon processes. We show the importance of this correction by studying potassium-doped picene (K_3 picene), recently claimed to be superconductor with T_c of up to 18 K. The Hamiltonian parameters are derived from ab-initio density functional theory, and the lattice model is solved by dynamical mean-field theory. Our calculations include the effects of electron-electron interactions and local electron-phonon couplings. Even with the inclusion of a strongly coupled molecular phonon, the Hubbard repulsion prevails and the system is an insulator with a small Mott gap of $\approx$0.2 eV. This work founds the basis of more reliable low-energy electron-phonon models and calls for a reinvestigation of the theoretical results obtained so far from ab-initio parametrizations of systems with strong electron-electron and electron-phonon couplings.

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Dynamics and Transport in Spin Orbit Coupled BECs

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I will describe experiments performed in my group studying dynamics and transport phenomena in spin-orbit coupled Bose-Einstein condensates (SOC-BEC). Our experimental setup[1, 2] creates optically trapped ^{87}Rb BECs, with synthetic gauge fields and spin-orbit coupling induced by optical Raman transitions. In one experiment[1], we study BEC transport in the synthetic "dressed" bandstructure, and realize a fully tunable Landau-Zener (LZ) transition between the dressed bands. We also study the breakdown of the (adiabatic) spin-momentum locking characteristic of SOC-BEC in the (non-adiabatic) LZ regime. In the second experiment[3], we use spin-dependent synthetic electric field generated by dynamically varying the SOC Raman coupling to induce a spin-dipole mode (SDM, opposite oscillations between two spin components) and thus an AC spin current in the trap. We observe that SOC significantly enhance the damping of BEC momentum in SDM, and qualitatively changes the dominant mechanisms of spin current relaxation from collision-induced thermalization for bare BECs to momentum damping for dressed BECs. Our work reveals rich interplay between SOC and atom-atom interactions in a superfluidic BEC, and may enable quantum simulation of spin transport phenomena previously studied in solid state spintronics.

These experiments are based on the thesis work of PhD students A.Olson, R.Niffenegger and C. Li. We also acknoledge theoretical discussions and collaborations with S. Wang, C. Greene, C. Qu, C. Zhang, H. Zhai and Y. Lyanda-Geller.

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Mapping the Occupied Spectral Function of a Fermi gas in the BCS-BEC Crossover

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Ultracold gases of fermionic atoms with tunable interactions provide a powerful tool for investigating and understanding strong correlations in fermions. In such systems, it is possible to tune the scattering length through a Feshbach resonance, thereby realizing a smooth crossover from the physics of Cooper pairs to that of condensed bosonic molecules (BCS-BEC crossover). While the ground state of this crossover is always a condensate of paired fermions, the normal state must evolve from a Fermi liquid on the BCS side to a Bose gas of molecules on the BEC side. How this occurs is still largely unknown. We explore this question using atom photoemission spectroscopy of a nearly homogeneous gas above Tc at many interaction strengths in the crossover. Inspired by angle-resolved photoemission spectroscopy (ARPES) used to probe condensed matter systems, atom photoemission spectroscopy probes the distribution of single particle energies and momenta in an ultracold gas. We find that our data fit well to a function that includes a positively dispersing peak and a broad, asymmetric background. The spectral weight of the positively dispersing park vanishes as the strength of interactions are modified, signaling a breakdown of a Fermi liquid description.

Mass Renormalizations and Uncoventional Pairing in Multiband Superconducting Iron Pnictides - a Phenomenological Approach

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Combining density functional theory (DFT) calculations of the density of states (DOS) and plasma frequencies with experimental thermodynamic and optical data, such as electronic specific heat and penetration depth, as well as available ARPES and dHvA data taken from the literature, we estimate both the high-energy (Coulomb, Hund's rule coupling) and low-energy (el-boson coupling) electronic mass renormalization for several typical Fe-pnictides with $T_c < 40$ K, focusing on AFe_2As_2 (A=K,Rb,Cs), (Ca,Na)122, (Ba,K)122, LiFeAs, and $LaFeO_{1-x}F_xAs$ with and without As-vacancies [1]. Using multiband Eliashberg theory we show that these systems can NOT be described by a very strong el-boson coupling constant $\lambda \gtrsim 2$ or even larger as often proposed in the literature [2], being in conflict with the significant high-energy mass renormalization as seen by ARPES and optics. Instead, an intermediate $s_\pm$ coupling regime is realized, essentially based on interband spin fluctuations from at least one predominant pair of bands. In some cases, e.g. (Ca,Na)122, there is also a non-negligible intraband el-phonon or el-orbital fluctuation contribution [3]. The coexistence of magnetic As-vacancies and high-T_c superconductivity for $LaFeO_{1-x}F_xAs_{1-\delta}$ [4]-[6] probably excludes an orbital fluctuation dominated s_{++} scenario [7] at least for that special compound. Difficulties of the standard DFT based results with respect to calculated and empirical partial DOS and Fermi surface cross sections are discussed in terms of orbital dependent correlation effects as well as in terms of additional surface effects probably observed in recent ARPES measurements [8].

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Witnessing quasi-particles in a strongly correlated electron system

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This presentation will focus on our recent results in Pump&Probe broadband spectroscopy on cuprates. The interaction between phonons and high-energy excitation of electronic origin in cuprates is studied in two compounds. In a archetypal strongly correlated charge-transfer insulator (La2CuO4), with the aid of a general theoretical framework (Hubbard Holstein Hamiltonian), we show that the interaction between electrons and bosons manifest itself directly in the photo-excitation processes of a correlated material and pilots the formation of itinerant quasi-particles which are suddenly dressed (¡100 fs) by an ultrafast reaction of the bosonic field. In optimally doped YBCO we combine coherent vibrational time-domain spectroscopy with density functional and dynamical mean field theory calculations to establish a direct link between the c-axis phonon modes and the in-plane electronic charge excitations in optimally doped YBCO.

Metal-to-superconductor transition, mesoscopic disorder and intrinsic charge instability in oxide heterostructures

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Keywords: oxide heterostructures, electronic phase separation, inhomogeneous superconductivity, quantum criticality

Motivated by experiments in oxide interfaces like $LaAlO_3/SrTiO_3$ or $LaTiO_3/SrTiO_3$ (LXO/STO) heterostructures, we investigate the occurrence of a metal-to-superconductor transition in a two-dimensional electron system with disorder on the mesoscopic scale and possible microscopic mechanisms for electronic phase separation (EPS) based on Rashba spin-orbit coupling (RSOC) [1,2] and/or electrostatic electron confinement at the interface [3]. Disorder induces a distribution of local superconducting critical temperatures accounting well for the transport (resistivity [4] and Hall [5]) and tunnel spectrosopy [6]. With lowering the temperature, global superconductivity establishes as soon as percolation occurs within the superconducting clusters.

Both RSOC and electrostatic confinement could provide an intrinsic mechanism for the observed inhomogeneous phases at the LAO/STO or LTO/STO interfaces and open the way to new interpretations of the observed quantum critical behaviour of LTO/STO [6]. We investigate the effects of temperature and magnetic field on the charge instability finding a novel type of quantum critical point related to the vanishing of the critical temperature of the EPS [2,3].

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Fe-based superconductors: role of the magnetic impurities

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Superconductors with different gap symmetries behave differently being subject to the disorder. It is especially important to determining this exact behavior in the Fe-based materials where both the order parameter symmetry and the mechanism of superconductivity are unknown. Here we analyze how the magnetic disorder affects the low-energy properties of the two-band $s_{\pm}$ and s_{++} models. In a standard case, T_c is suppressed approximately following the Abrikosov-Gor'kov trend. There are, however, few exceptional cases with the saturation of T_c for the finite amount of impurities: 1) $s_{\pm}$ superconductor with the purely interband impurity scattering potential or with the unitary impurities, 2) s_{++} state with the interband scattering only. We show that the latter unusual behavior is due to the $s_{++} \to s_{\pm}$ transition similar to the $s_{\pm} \to s_{++}$ transition caused by nonmagnetic impurities [1]. Since this transition goes through the gapless regime, there should be clear signatures in the thermodynamics of the system. Therefore, it may manifest itself in optical and tunneling experiments, as well as in a photoemission and thermal conductivity on Fe-based superconductors and other multiband systems.

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Many-body Anderson localization of strongly interacting Bose-Einstein condensates in disordered lattices

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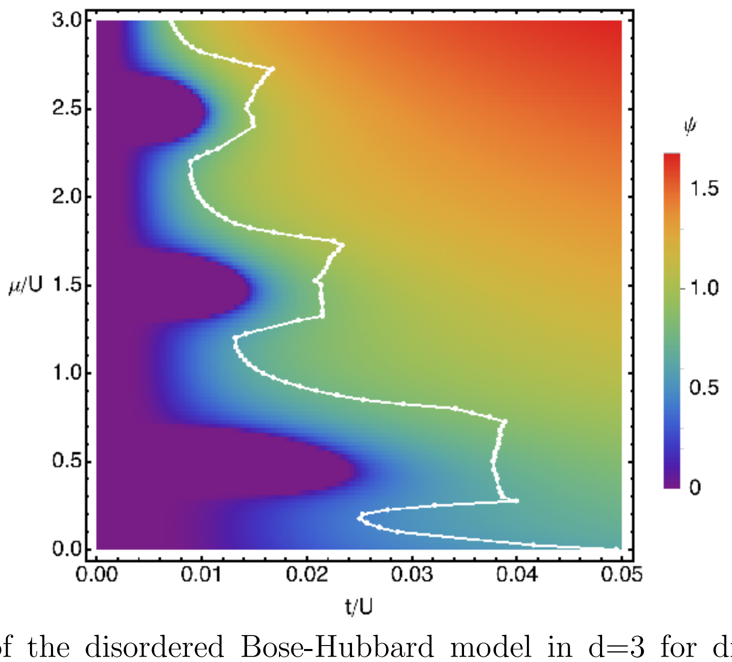
We have developed the transport theory for a Bose gas in the disordered Bose-Hubbard model in the regime of strong, repulsive interactions, i.e. in the vicinity of the Mott lobes of vanishing Bose-Einstein condensate (BEC) amplitude. In contrast to previous approaches, the Bose glass phase in a disordered system should be defined not via a vanishing averaged BEC amplitude with finite compressibility, but via vanishing superfluid transport. That is, we define the Bose glass phase as the state where the averaged BEC amplitude is finite, but the superfluid current vanishes due to Anderson localization of the interacting BEC wave functions and its many-body excitations (Anderson localized, BEC puddles). The theory is based on a calculation of the on-site many-body eigenstates within a stochastic mean-field theory which treats the on-site Hubbard interaction exactly by diagonalizing the local part of the Bose-Hubbard Hamitonian exactly in Fock space. Non-local effects of the interaction are neglected in analogy to dynamical mean-field theory (DMFT). The transport theory for these hopping many-body states, including quantum interference processes (Cooperons) is formulated as a generalization of the self-consistent theory of Anderson localization. The theory describes semiquantitatively the Mott localized phase (Mott lobes), the superfluid phase and the Bose glass phase as well as the respective phase transitions. In particular, the theory obeys the theorem of inclusions which states that in a disordered system there is no direct transition from the Mott phase to the superfluid phase.



Phase diagram of the disordered Bose-Hubbard model in d=3 for disorder parameter $W/U = 0.6$. U: Hubbard repulsion, t: hopping, μ: chem.potential. The color code represents the modulus of the averaged BEC order parameter. White line with dots: phase transition line between the superfluid (right) and the Bose glass (left of the line).

Excitonic condensation of strongly correlated electrons

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Competition of several atomic multiplets in materials with strongly correlated electrons, e.g., close to a spin-state transition, may result in an instability towards long-range ordering. We have investigated the minimal model exhibiting such behavior, the two-band Hubbard model[1, 2]. Besides a conventional high-spin–low-spin checker-board order we found a behavior that can be described as a condensation of spinful excitons. We will discuss the physics of the excitonic condensation and present results obtained with the dynamical mean-field theory. We will also briefly mention the excitonic solutions we have obtained with LDA+U for real materials and point out the rich physics arising from orbital degeneracy in these systems.

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Optical Lattices with Large Scattering Length

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I will discuss a new proposal to go beyond the standard way of thinking of atoms in optical lattices by bringing in ideas from few-body physics. I will consider a setup where one atomic species is trapped in a lattice at full filling while another is untrapped (does not see the optical lattice) but has an s-wave contact interaction with the first one. If the interspecies scattering length is positive and on the order of the lattice spacing then the usual two-body bound (dimer) states overlap forming a polyatomic molecule extending over the entire lattice, which can also be viewed as a band solid for the untrapped species, where the trapped atoms play the role of ions. This setup requires large scattering lengths but minimises losses, does not need higher bands and adds new degrees of freedom which cannot easily be described in terms of lattice variables. As an example I show how to create an electron-phonon quantum simulator which exhibits renormalization of the phonon frequencies due to electron-ion interactions, Peierls instability, and where the effective phonon Hamiltonian can be mapped in some cases to a quantum transverse Ising model.

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Mobility edge of atoms in laser speckle potentials: exact calculations versus self-consistent approaches

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A major experimental challenge with cold atoms is to study Anderson localization of three-dimensional samples exposed to laser speckles potentials. These patterns are characterized by an exponential on-site distribution $P(V)$ and finite spatial correlations.

In this talk I will present numerically exact results [1] for the position of the mobility edge obtained by discretizing the system on a finite grid and applying the transfer matrix technique to the effective Anderson model. These results deviate significantly from previous implementations of the self-consistent theory of localization and I will explain the reasons of the discrepancy. In particular the asymmetry of $P(V) \neq P(-V)$ plays a key role leading to completely different predictions for the mobility edge of atoms in blue and in red speckles.

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Orbital magnetism with SU(N) fermions

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I will report on recent experiments performed at LENS with ultracold ^{173}Yb Fermi gases. These two-electron atoms are characterized by a large nuclear spin and highly-symmetric interactions, which result in the possibility of performing quantum simulations of multi-component fermionic systems with intrinsic and tunable SU(N) interaction symmetry. By controlling the number of spin components N, we have studied how static and dynamic properties of strongly-correlated 1D liquids of ^{173}Yb fermions change with N, evidencing for the first time intriguing effects caused by the interplay between interactions, low-dimensionality and quantum statistics [1].

In addition to their nuclear spin, two-electron fermions offer experimental access to supplementary degrees of freedom, in particular to long-lived electronically-excited states. In this talk I will focus on our recent observation of fast, coherent spin-exchange oscillations between two ^{173}Yb atoms in different electronic orbitals [2], obtained by coherent control of the atomic state on the ultranarrow $^1S_0 \rightarrow {}^3P_0$ clock transition.

These experiments disclose some of the new possibilities offered by two-electron atoms for quantum simulation, opening exciting directions connected e.g. to exotic quantum magnetism and to the investigation of many-body physics of systems with SU(N) symmetries.

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Electrodynamics of hetero-structured high temperature superconductors

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Both the iron-based and the cuprate high temperature superconductors, are intrinsically multi-layered materials. Particular efforts have thus been devoted to the deposition of thin superconducting films and to artificially synthesize heterostructures based onto different superconducting materials. The study of these systems can provide new clues to the understanding of the general mechanism of high temperature superconductivity while offering the possibility to tailor important superconducting properties. An important example is provided by Co-doped Ba122 superlattices, where it was shown that heterostructuring the pristine superconducting compound can result in a substantial enhancement of the upper critical field, due to controlled flux pinning[1]. On the other hand, in cuprates, the fabrication of artificial interfaces between the insulating $CaCuO_3$ and $SrTiO_3$ compounds, results in superconducting interfaces, analogous to the Copper-Oxide planes of the cuprates[2]. We address here the electrodynamics of both these classes of heterostructured superconductors[3].

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Interaction and Disorder Effects Across BCS-BEC Crossover in Three- and Two-Dimensional Fermi Gases

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We investigate the effect of static impurities in three- and two-dimensional ultracold atomic Fermi gases. We incorporate disorder from impurities through fluctuations [1, 2] and study its effects on the BCS-BEC crossover. We analyze the effect of quenched disorder for various physical quantities such as chemical potential, pairing gap, density of states, spectral function, and ground-state energy. We extend our study further towards the experimentally viable quantities such as condensate fraction, sound velocity and Landau critical velocity. The results are presented as a function of binding energy (in 2D) and 3D scattering length (in 3D). We observe negligible effect of disorder in 2D for BCS Cooper pairs and considerable amount of depletion in the BEC regime but intriguingly the results also reveal that disorder effect is masked at the crossover region [2, 3, 4]

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Boosting the critical temperature in Co-doped Ba122: a spectroscopic view.

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There have been several reports on the effects of annealing on enhancing the critical temperature in $BaFe_2As_2$ iron-pnictide superconductors [1-3]. Here we present transport and optical spectroscopy experiments on as-grown and annealed $BaFe_{2-x}Co_xAs_2$ crystals (x=0.2). Resistivity measurements show an increase in the superconducting critical temperature (T_c) from 18 K to 26 K, but susceptibility measurements indicate that the bulk of the material only becomes fully superconducting at somewhat lower temperatures (15 K and 19 K respectively).
To elucidate the origin of this T_c increase we investigate the normal state charge dynamics using optical spectroscopy. Even though the dc resistivity does not display striking differences upon annealing, the reflectivity very clearly displays a reduction of scattering as evidenced by a sharper plasma edge and an increase of the low frequency reflectivity. A more detailed analysis of the normal state optical conductivity unveils evidence for the emergence of Fermi liquid like behavior in the annealed sample.

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