Workshop on

Quantum Simulations with Ultracold Atoms

(Trieste, 16-20 July 2012)

TALKS

G. Bruun: *Repulsive polarons in a strongly interacting Fermi gas*

I discuss the existence of long-lived repulsive as well as attractive polarons in a strongly interacting Fermi gas. The energy, lifetime, and quasiparticle residue of the polarons are calculated, and I show show how they accurately describe experimental data. Finally, I discuss possible consequences of these results regarding observing itinerant ferromagnetism in atomic gases.

A. Celi: *Quantum simulation of an Extra Dimension*

Due to the great experimental developments in cold

atoms physics, a great variety of extended Hubbard models can be engineered nowadays using optical lattices. In particular, the presence of internal degrees of freedom that may be controlled (almost) at will, offers new opportunities to quantum simulation. Among them, the possibility of simulating dynamics in more then three spatial dimensions. I will explain how, and under which feasible conditions on the hopping, the internal degrees of freedom can be reinterpreted as displacement in an extra-dimension. Examples of single-particle and many-body signatures are discussed in two alternative experimental set-ups. I will conclude mentioning how similar ideas can be applied to simulate systems with no-standard boundary conditions.

C. Chin: *Exploring Universal Quantum Physics in few- and many-body atomic systems*

Recent cold atom researches are reaching out far beyond the realm that was conventionally viewed as atomic physics. Many long standing issues in other physics disciplines or in Gedanken-experiments are nowadays common targets of cold atom physicists. Two prominent examples will motivate this talk: BEC-BCS crossover and Efimov physics. Here, cold atoms are employed to

emulate electrons in superconductors, and nucleons in nuclear reactions, respectively.
The ability to emulate exotic or thought systems using cold atoms stems from the precisely determined, simple, and tunable interaction properties of cold atoms. New experimental tools have also been devised toward an ultimate goal: a complete control and a complete characterization of a few- or many-body quantum system. We are tantalizingly close to this major milestone, and will soon open new venues to explore new quantum phenomena that may (or may not!) exist in scientists' dreams.

E. Demler: *Exploring topology with synthetic matter*

N. Cooper: *Mapping the Berry Curvature of Optical Lattices*

I shall describe a general method by which experiments on ultracold gases can be used to determine the topological properties of the energy bands of optical lattices, as represented by the map of the Berry curvature across the Brillouin zone. The Berry curvature modifies the semiclassical dynamics of a wave packet undergoing Bloch oscillations. I shall illustrate the consequences of non-zero Berry curvature for an asymmetric hexagonal lattice, and for an "optical flux lattice" for which the Chern number is nonzero.

F. Ferlaino: *Bose-Einstein Condensation of Erbium*

We report on the production of the first Bose-Einstein condensate of erbium [1]. Erbium is a very special multi-valence-electron atom, belonging to the lanthanide series. It possesses a strongly magnetic dipolar character, a rich energy level diagram, and various isotopes, among which one has fermionic nature. Despite the complex atomic properties of such unconventional species, we find a surprisingly simple and efficient approach to reach quantum degeneracy by means of laser cooling on a narrow-line transition and standard evaporative cooling techniques. We observe favorable scattering properties of 168Er, resulting in remarkably high evaporation efficiency and in a large number of Feshbach resonances at very low magnetic field values (around 1 G). All these desirable properties make Er a dream system for ultracold quantum gas experiments.

[1] K. Aikawa et al., Phys. Rev. Lett. **108**, 210401 (2012)

T. Giamarchi: *Dirty bosons in one dimension*

Combination of disorder and interactions lead to novel physics effects and phases. This particularly spectacular in the case of bosons, for which the competition between superfluidity and Anderson localization can lead to a transition between a superfluid and a localized (Bose Glass) phase [1]. I will discuss here the phase diagram for one dimensional bosons in the presence of disorder, and discuss the possibility that a transition between two different Bose glass phases might exist [2]. I will also discuss the similarities and differences between disordered and quasiperiodic potentials, as well as the connection to cold atom experiments.

[1] T. Giamarchi and H. J. Schulz, Phys. Rev. B 37, 325 (1988); M. P. A. Fisher et al. , Phys. Rev. B **40**, 546 (1989)
[2] Z. Ristivojevic, A. Petkovic, P. Le Doussal, and T. Giamarchi, arxiv/1205.2105, to be published in PRL

N. Goldman: *Identifying Topological Edge States in 2D Optical Lattices using Light Scattering*

Recently, several experiments have successfully created synthetic gauge potentials for cold atoms in optical lattices [1,2,3]. These important achievements have opened the path to the future realization of topological insulating phases in clean and controllable setups. In parallel to this outstanding experimental progress, one fundamental issue is to identify observables that provide unambiguous signatures of topological phases in a cold-atom environment.

In this talk, I will introduce an efficient and realistic method to extract and identify topological edge states (i.e. the hallmark of topological insulating phases) in a two-dimension optical lattice subjected to a uniform magnetic field [4]. Our scheme, which could be applied to a wide family of cold-atom topological phases, is based on a generalization of Bragg spectroscopy sensitive to angular momentum. We demonstrate that using a well-designed laser probe, the Bragg spectra provide an unambiguous signature of the topological edge states that establishes their chiral nature. This signature remains clear for a variety of boundaries, from a hard wall to a smooth harmonic potential added on top of the optical lattice. Since the Bragg signal is very weak, we introduce a “shelving method”, based on Raman transitions, which transfers angular momentum and changes the internal atomic state simultaneously. This scheme allows to detect the weak signal from the selected edge states on a dark background, and drastically improves the detectivity. It also leads to the possibility to directly visualize the topological edge states, using in situ imaging, offering a unique and instructive view on topological insulating phases.

[1] M. Aidelsburger et al., Phys. Rev. Lett. **107**, 255301 (2011)
[2] K. Jiménez-García et al., Phys. Rev. Lett. **108**, 225303 (2012)
[3] J. Struck et al. Phys. Rev. Lett. **108**, 225304 (2012)
[4] N. Goldman, J. Beugnon, and F. Gerbier, Phys. Rev. Lett. **108**, 255303 (2012)

<u>S. Hofferberth:</u> *Rydberg-Rydberg interactions in ultracold atomic gases*

The strong, long-range interactions between Rydberg atoms enable the realization of novel many-body cooperative or collective effects in ultra-cold atomic gases. We present two recent experimental results. Firstly, we discuss the application of Stark-tuned Förster resonances to tune the Rydberg-Rydberg interaction and the mapping of these interactions on ground state ensembles using Rydberg dressing. Secondly, we show that the Rydberg blockade effect can be used to realize optical nonlinearities on the single photon level, which enables the creation of highly non-classical light using ultracold Rydberg gases.

M. Koehl: *Two-dimensional Fermi gases*

Pairing of fermions is ubiquitous in nature and it is responsible for a large variety of fascinating phenomena like superconductivity, superfluidity of 3He, the anomalous rotation of neutron stars, and the BEC-BCS crossover in strongly interacting Fermi gases. When confined to two dimensions, interacting many-body systems bear even more subtle effects, many of which lack understanding at a fundamental level. Most striking is the, yet unexplained, effect of high-temperature superconductivity in cuprates, which is intimately related to the two-dimensional geometry of the crystal structure. In particular, the questions how many-body pairing is established at high temperature and whether it precedes superconductivity are crucial to be answered. We report on the observation of pairing in trapped two-dimensional atomic Fermi gas in the regime of strong coupling. We perform momentum-resolved photoemission spectroscopy to measure the spectral function of the gas and we detect a many-body pairing gap above the superfluid transition temperature. Moreover, using the same technique, we investigate spin-imbalanced Fermi gases and find evidence for the formation of polarons and their crossover to a dimer state in two dimensions. Our observations mark a

significant step in the emulation of layered two-dimensional strongly correlated superconductors using ultracold atomic gases.

R. Konik: *Non-Equilibrium Behavior and Thermalization in 1D Bose Gases*

Using a new numerical renormalization group based on exploiting an underlying exactly solvable nonrelativistic theory, we study the equilibrium properties and out-of-equilibrium dynamics of interacting many-body quantum systems. Focusing on the example of the Lieb-Liniger model we study quantum quenches with a focus on protocols in which the gas is released from a parabolic trap. Our method allows one not only to accurately describe the equilibrium state of the gas in the trap, but also to track the post-quench dynamics all the way to infinite time. Exploiting integrability, we are also able to exhibit a general protocol for the explicit construction of the generalized Gibbs ensemble, which is a candidate to govern the equilibriation of the trapped gas after its release. This construction does not rely on the underlying Hamiltonian being quadratic and works for arbitrary initial conditions. By comparing the predictions of equilibration from this ensemble against

the long time dynamics observed in our method, we find that it is considerably more accurate than the effective grand canonical ensemble.

S. Kuhr: *Probing the dynamics of strongly correlated quantum systems with single-atom resolution*

Ultracold atoms in optical lattices are a versatile tool to investigate fundamental properties of quantum many body systems. We demonstrate how the control of such systems can be extended down to the most fundamental level of single atomic spins at specific lattice sites. Using a high-resolution optical imaging system, we were able to obtain fluorescence images of strongly interacting bosonic Mott insulators with single-atom and single-site resolution [1]. This technique allowed us to directly see individual quantum fluctuations as correlated particle-hole pairs [2], or to witness the spreading of correlated quasi-particles after a parameter quench [3]. Using a single-site addressing technique [4], we prepared a single spin impurity and tracked it as it spreads through either one-dimensional Mott-insulating or superfluid systems. We also used the high-resolution imaging technique for in-situ detection of individual Rydberg excitations in a 2D atomic Mott insulator, and we could directly observe Rydberg blockade and crystalline states of the excitations.

[1] J. F. Sherson et al., Nature **467**, 68 (2010)
[2] M. Cheneau et al., Nature **481**, 484 (2012)
[3] M. Endres et al., Science **334**, 200 (2011)
[4] C. Weitenberg et al., Nature **471**, 319 (2011)

B. Laburthe-Tolra: *Dipolar Chromium BECs and Magnetism*

Bose-Einstein condensates (BECs) made of 52Cr atoms host new phenomena, due to the existence of long-ranged, anisotropic dipole-dipole interactions. I will for example describe the modification of collective excitations due to dipolar interactions [1], as well as the existence of an anisotropic speed of sound [2] revealed by means of Bragg spectroscopy.
In this talk, I will mainly discuss the effect of dipolar interactions on the properties of multi-component (spinor) Cr condensates at very low magnetic fields. Due to its anisotropy, the dipole interaction introduces magnetization-changing collisions, which frees the magnetization of the gas. Hence, dipolar BECs at low field are excellent systems to study magnetism.
We have investigated the magnetic phase diagram as a function of temperature and magnetic field. At large

enough magnetic fields, we observe a spontaneous magnetization of the cloud when BEC is reached, which reveals the ferromagnetic nature of BECs [3]. At extremely low magnetic fields, however, the BEC spontaneously depolarizes, due to a phase transition when (anti-ferromagnetic) spin-dependent interactions overwhelm the linear Zeeman effect [4].

I will finally describe the magnetism of a Cr BEC loaded in 3D optical lattices, which has direct analogies to the Heisenberg model of magnetism. We have investigated the magnetic ground state at low magnetic field, as well as the relaxation of a spin-excited state. Magnetization relaxation shows a pronounced resonant character as a function of magnetic field, when the energy released in dipolar relaxation matches a band excitation energy. These dipolar resonances are anisotropic, due to the anisotropy of dipolar interactions.

[1] G. Bismut et al., Phys. Rev. Lett. **105**, 040404 (2010)
[2] G. Bismut et al., arXiv:1205.6305
[3] B. Pasquiou et al., Phys. Rev. Lett. **108**, 045307 (2012)
[4] B. Pasquiou et al., Phys. Rev. Lett. **106**, 255303 (2011)

I. Lesanovsky: *Simulation of interacting spins and anyons with Rydberg lattice gases*

During the past years the field of ultra cold atomic physics has produced exciting insights into the structure and dynamics of many-body quantum systems. The reason for this success story is rooted in the versatility offered by ultra cold atoms, such as the tunability of their interactions and the advanced techniques that have been developed for their trapping and coherent manipulation.

At present the majority of ultra cold atoms experiments is carried out with ground state atoms. Since very recently, however, there is a growing initiative aiming towards exploiting the unique properties of atoms in highly excited states. Those so-called Rydberg atoms are blessed with remarkable features such as strong and long-ranged interactions together with comparatively long coherence times.

In this talk I discuss static and dynamic many-body phenomena that can be explored with Rydberg atoms in low dimensional lattices. Specifically, I will analyze dynamic and static properties of spin models that can be implemented with a dense Rydberg lattice gas. Moreover, I will show that a one-dimensional Rydberg lattice naturally hosts interacting Fibonacci anyons and therefore constitutes a platform for the study of exotic forms of quantum matter.

G. Modugno: *Experiments with disordered, interacting Bose gases*

The interplay of disorder and nonlinearities is still not fully understood, because of the difficulty of controlling independently the parameters of most physical systems. I will describe how we are exploring this interplay with a Bose gas with tunable interaction and disordered optical potentials. In particular, we study the conductive and insulating phases in 1D from weak to strong interactions. We also study the spreading of matter wavepackets in presence of disorder, interaction and noise.

M.K. Oberthaler: *Bifurcation - in the classical and quantum regime*

We report on our recent experimental results obtained in the context of bosonic internal Josephson junctions which allow for the realization of a classical bifurcation scenario. The classical [1] as well as the quantum dynamics is experimentally investigated in the situation of a single external mode and the results are in good agreement with the theoretical expectations. By adding external degrees of freedom a situation can be reached where the quantum dynamics in a quench through a quantum phase transition can be studied [2]. We will present our recent results on scaling of the excitations generated by quenching through a critical point with different speeds and compare with the expectation given by the Kibble Zurek mechanism.

[1] T. Zibold et al., Phys. Rev. Lett. **105**, 204101 (2010)
[2] J. Sabbatini, W.H. Zurek, and M.J. Davis, Phys. Rev. Lett. **107**, 230402 (2011)

G. Ortiz: *Duality as a Tool for Quantum Simulation of Topological Matter*

Dualities appear in nearly all disciplines of physics and play a central role in statistical mechanics and field theory. I will start discussing in a pedagogical manner our bond-algebraic techniques which provide a simple unifying framework for the detection and treatment of dualities. Duality transformations constitute fundamental tools for quantum simulation since they represent dictionaries allowing translation to the simulator language. I will then describe some basic notions of topological quantum matter needed for quantum simulation of engineered models displaying such an order. Motivated by the prospect of attaining Majorana modes at the ends of nanowires, I will then analyze interacting Majorana systems on general networks and lattices and derive various universal spin duals. Finally, I will show how to engineer quantum simulators out of these Majorana networks.

<u>T. Pohl:</u> *Quantum Simulations of and with Rydberg Atoms*

By virtue of their exaggerated properties, Rydberg atoms have recently emerged as promising building blocks for applications in quantum information and quantum optics.

In this talk, we will explore such prospects for quantum simulations of strongly interacting quantum many-body systems. The van der Waals interaction between Rydberg states exceeds that of ground state atoms by many orders of magnitude and extends over long distances that greatly exceeds typical interatomic distances in ultracold atomic gases.

In the first part of the talk, I will consider the excitation dynamics of such systems, and discuss different many-phases emerging from the coherent laser-coupling to strongly interacting Rydberg states. This fast dynamics bears analogies to long-interacting quantum magnets. Complementary, the second part, will focus on longer timescales, where the Rydberg-induced long-range interactions between atoms in a Bose-Einstein condensate lead to the formation of supersolid states. Here, I will present a detailed study of the corresponding phase diagram under weak and strong coupling conditions and discuss (dis)similarities to the physics of solid Helium.

A. Polkovnikov: *Phase transitions in real time following a quantum quench*

In this talk I will discuss examples of phase transitions occurring in real time in thermally isolated systems following a quantum quench. I will argue that the concepts usually associated with equilibrium continuous phase transitions (renormalization group analysis, break down of the high temperature expansion, Fisher zeros and others) can be extended to the real time domain. I will show how one can approach non-equilibrium quantum phase transition by post-selection, which can be used for effectively cooling the system. I will demonstrate these general ideas using specific examples of quenches in two-dimensional superfluids, transverse field Ising model and periodically driven spin chains.

N. Prokofiev: *Higgs amplitude mode in a 2D superfluid*

We demonstrate existence of a well-defined Higgs resonance in two-dimensional relativistic field theories based on analytically continued results from quantum Monte Carlo simulations of the Bose-Hubbard model in the vicinity of the superfluid-Mott insulator quantum critical point, featuring emergent particle-hole symmetry and Lorentz-invariance.

The Higgs boson, seen as a resonance in the spectral density for kinetic energy, is quickly pushed to high energies in the superfluid phase and disappears by merging with the broad secondary peak at the characteristic interaction scale. Simulations of a trapped system of ultra-cold Rb-87 atoms demonstrate that the low-frequency resonance feature is lost for typical experimental parameters, while the characteristic frequency for the onset of strong response is preserved.

G. Pupillo: *Rydberg-dressed atoms: from many-body phases to molecular cooling*

We discuss recent theoretical progress with groundstate alkali atoms weakly dressed by an off-resonant laser beam to a Rydberg state. We demonstrate that laser-dressing can induce novel exotic many-body phenomena in a gas of ultracold atoms, such as a quantum phase transition from a BEC to a free-space supersolid crystal. Engineered interactions between Rydberg-dressed atoms and polar molecules can be used to cool the latter down from mK to μK temperatures. This can be of use for reaching the ultracold regime with non-bialkali polar molecules.

M. Rizzi: *An optical-lattice-based quantum simulator for relativistic field theories and topological insulators*

We present a proposal for a versatile cold-atom-based quantum simulator of relativistic fermionic theories and topological insulators in arbitrary dimensions. The setup consists of a spin-independent optical lattice that traps a collection of hyperfine states of the same alkaline atom, to which the different degrees of freedom of the field theory to be simulated are then mapped.

We show that the combination of bi-chromatic optical lattices with Raman transitions can allow the engineering of a spin-dependent tunneling of the atoms between neighboring lattice sites. These assisted-hopping processes can be employed for the quantum simulation of various interesting models, ranging from noninteracting relativistic fermionic theories to topological insulators.
We present a toolbox for the realization of different types of relativistic lattice fermions, which can then be exploited to synthesize the majority of phases in the periodic table of topological insulators.

[1] L. Mazza et al. New J. Phys. **14**, 015007 (2012)
[2] A. Bermudez et al., Phys. Rev. Lett. **105**, 190404 (2010)
[3] L. Mazza et al., Phys. Rev. A **82**, 043629 (2010)

<u>C.A.R. Sa De Melo:</u> *Who is the Lord of the Rings in the Zeeman-spin-orbit Saga: Majorana, Dirac or Lifshitz?*

I discuss the simultaneous effects of Zeeman and spin-orbit fields during the evolution from BCS to BEC superfluidity for ultra-cold fermions. I focus on spin-orbit couplings with equal Rashba and Dresselhaus strengths, and show that topological phase transitions of the Lifshitz class occur through the emergence of Majorana and/or Dirac fermions as Zeeman and spin-orbit fields are varied. Topological quantum phase transitions in superfluids with non-s-wave order parameters have been conjectured theoretically for p-wave and d-wave systems for many years, but never observed experimentally due to the absence of tunable parameters. However, Zeeman or spin-orbit fields and interactions can be tuned in the context of ultra-cold atoms and allow for the visitation of several different phases. For systems with zero Zeeman field, the evolution from BCS to BEC superfluidity in the presence of spin-orbit effects is only a crossover as the system remains fully gapped, even though a triplet component of the order parameter emerges. In contrast, for finite Zeeman fields, spin-orbit coupling induces a triplet component in the order parameter that produces nodes in the quasiparticle excitation spectrum leading to bulk topological phase transitions of the Lifshitz type. Additionally, a fully gapped phase exists, where a crossover from indirect to direct gap occurs. For spin-orbit couplings with equal Rashba and Dresselhaus strengths the nodal quasi-particles are Dirac fermions that live at and in the vicinity of rings of nodes. Transitions from and to nodal phases can occur via the emergence of zero-mode Majorana fermions at phase boundaries, where rings of nodes of Dirac fermions annihilate. Lastly, I characterize different phases via spectroscopic and thermodynamic properties and conclude that Lifshitz is the “Lord of the Rings”.

C. Salomon: *Thermodynamics of Bose and Fermi Quantum Gases*

Ultracold dilute atomic gases can be considered as model systems to address some pending problem in Many-Body physics that occur in condensed matter systems, nuclear physics, and astrophysics. We have developed a general method to probe with high precision the thermodynamics of locally homogeneous ultracold Bose and Fermi gases [1,2,3]. This method allows stringent tests of recent many-body theories. For attractive spin 1/2 fermions with tunable interaction (^6Li), we will show that the gas thermodynamic properties can continuously change from those of weakly interacting Cooper pairs described by Bardeen-Cooper-Schrieffer theory to those of strongly bound molecules undergoing Bose-Einstein condensation. First, we focus on the finite-temperature Equation of State (EoS) of the unpolarized unitary gas. Surprisingly, the low-temperature properties of the strongly interacting normal phase are well described by Fermi liquid theory [3] and we localize the superfluid phase transition. A detailed comparison with theories including recent diagrammatic Monte-Carlo calculations will be presented. Moving away from the unitary gas, the Lee-Huang-Yang and Lee-Yang beyond-mean-field corrections for low density bosonic and fermionic superfluids are quantitatively measured for the first time. Finally we probe the unitary Bose gas and measure the temperature dependence of the three-body decay rate.

[1] S. Nascimbène et al., Nature **463**, 1057 (2010)
[2] N. Navon et al., Science **328**, 729 (2010)
[3] S. Nascimbène et al., Phys. Rev. Lett. **106**, 215303 (2011)

L. Santos: *Novel scenarios in ultra-cold lattice gases: Zig-zag optical lattices and gases with periodically modulated interactions*

Ultra-cold lattice gases offer a wide range of possibilities for control, even in real time, of the system parameters including the lattice geometry and the inter-particle interactions. In this talk I will comment on two interesting scenarios which are related, respectively, to the role played by the lattice geometry, and to the possibility of variating the inter-particle interactions in real time.
I will first address the case of ultra-cold bosons in one-

dimensional zig-zag lattices, showing that this geometry leads for unconstrained bosons to chiral superfluidity and to a Mott insulator for vanishingly small interactions. For bosons with a three-body hard-core constraint, the system presents a rich phase diagram, including a Haldane-insulator phase in absence of polar interactions.

In the second part of the talk I will comment on lattice gases with periodically modulated interactions. By means of a Floquet analysis we show that under proper conditions such a modulation results in a novel scenario for lattice gases, characterized by a non-linear hopping that depends on the occupation difference at neighboring sites. We show that this peculiar hopping results in a rich physics, including pair-superfluidity, defect-free Mott insulator states without particle-hole quantum fluctuations, and pure holon- and doublon-superfluids. We show that this physics may result in abrupt density drops in harmonically trapped lattice gases, which mark the boundary between holon- and doublon-superfluids.

G. Sierra: *Quantum spin analogues of Fractional Quantum Hall wave functions*

It has been long known the close relationship between chiral spin liquids and Fractional Quantum Hall systems. The most notorious examples are provided by the Haldane-Shastry wave function defined in 1D, and the Kalmeyer-Laughlin wave function in 2D. In this talk we shall present a unified picture of these examples within the framework of Conformal Field Theory. We shall also discuss further generalizations of these models to higher spin and non abelian versions related to the Moore-Read wave function.

A. Smerzi: *Entanglement, Distinguishability and Sub Shot-Noise Interferometry*

Entanglement is an algebraic property of quantum states. Its physical interpretation is typically related to non-locality. In our talk we will show that entanglement is physically related also with the concept of distinguishability of quantum states. The reason is that entangled states can evolve faster under unitary transformations than classical states. This has important implications in the theory of quantum Zeno dynamics as

well as in the theory of a parameter estimation. We will discuss a recent experiment along these directions where twin-matter waves have been created with trapped Bose-Einstein condensates.

A. Sommer: *Spin-Orbit Coupled Fermi Gases and the Evolution of Fermion Pairs from 3D to 2D*

The coupling of the spin of electrons to their motional state lies at the heart of recently discovered topological phases of matter. We generate spin-orbit coupling in an atomic Fermi gas of lithium-6 atoms using a Raman transition. The spin-orbit gap is detected via spin-injection spectroscopy, which characterizes the energy-momentum dispersion and spin composition of the quantum states. The spinful band structure of a spin-orbit coupled lattice is also measured, revealing a winding of the spin as a function of momentum. In a separate experiment, we study the binding energy of fermion pairs in the crossover from three to two dimensions. Dimensionality is tuned by varying the depth of a one-dimensional optical lattice. The binding energy is measured as a function of lattice depth and interaction strength and compared with theoretical predictions.

S. Stringari: *Spin-orbit coupled Bose-Einstein condensates*

In this talk I will present recent theoretical results concerning the phase diagram and the collective excitations of a spin-orbit coupled Bose-Einstein condensed gas with equal Rashba and Dresselhaus couplings. The phase diagram exhibits a rich structure including the occurrence of a tri-critical point where the stripe, the spin separated and the single minimum phases converge. The dynamic behavior of these systems is also investigated and the crucial role played by the spin orbit coupling in quenching the frequency of the elementary excitations is pointed out.

T. Takekoshi: *Ultracold dipolar bosonic molecules*

Dipolar quantum gas systems at ultralow temperatures are expected to exhibit novel many-body quantum phases as a result of the long-range and anisotropic dipole-dipole interaction. For our Rb-Cs mixture experiment the focus is on the creation of a bosonic quantum gas of polar ground-state RbCs molecules using Feshbach association and subsequent stimulated adiabatic Raman transfer (STIRAP). We have created a high phase-space density sample of ultracold RbCs Feshbach molecules from an ultracold mixture of Rb and Cs and have performed high-resolution molecular spectroscopy using the Feshbach molecules and have found intermediate electronically excited levels suitable for RbCs ground-state transfer. We have measured the binding energy of the RbCs rovibrational ground state in two-photon spectroscopy and have performed STIRAP experiments with transfer efficiencies of up to 90%. We have implemented an optical lattice with the ultimate aim to create a Mott-insulator state having precisely one atom of each species at each lattice site to improve the creation efficiency for the Feshbach molecules and the STIRAP transfer efficiency. Presently, we switch on the lattice after Feshbach molecule creation to localize the molecules and to prevent collisions. To improve the STIRAP efficiency we have set up ultra-stable optical resonators to which we lock the transfer lasers to reduce laser phase noise.

<u>L. Tarruell:</u> *Engineering Dirac points with ultracold fermions in optical lattices*

Dirac points lie at the heart of many fascinating phenomena in condensed matter physics, from massless electrons in graphene to the emergence of conducting edge states in topological insulators. At a Dirac point, two energy bands intersect linearly and the particles behave as relativistic Dirac fermions. In solids, the rigid structure of the material sets the mass and velocity of the particles, as well as their interactions. A different, highly flexible approach is to create model systems using fermionic atoms trapped in an optical lattice, a method which so far has only been applied to explore simple lattice structures. In my talk I will report on the creation of Dirac points with adjustable properties in a tunable honeycomb optical lattice. Using momentum-resolved interband transitions, we observe a minimum band gap inside the Brillouin zone at the position of the Dirac points. We exploit the unique tunability of our lattice potential to adjust the effective mass of the Dirac fermions by breaking the inversion symmetry of the lattice. Moreover, changing the lattice anisotropy allows us to move the position of the Dirac points inside the Brillouin zone. When increasing the anisotropy beyond a critical limit, the two Dirac points merge and annihilate each other. We map out this topological transition in lattice parameter space and find excellent agreement with ab initio calculations. Our results not only pave the way to model materials where the topology of the band structure plays a crucial role, but

also provide the possibility to explore many-body phases resulting from the interplay of complex lattice geometries with interactions.

M. Ueda: *Three Universal Trimers in Ultracold Atoms*

We discuss three distinct types of universal trimers: Efimov, Kartavtsev-Malykh, and crossover trimers. In mass-imbalaced systems, they appear in various parameter regimes and are universal in that they do not depend on short-range details other than the scattering length and the three-body parameter, whereas they are distinguished from each other in their scaling property. The Efimov, Kartavtsev-Malykh, and crossover trimers respectively feature discrete, continuous, and no scale invariance. On the other hand, in systems of identical atoms, there has been mounting evidence that the three-body parameter is nearly constant in log scale not only across different universal regimes of one atomic species but also across different atomic species. We report the result of our numerical calculations based on a realistic Helium potential in agreement with experiemental results.

C. Weitenberg: *Superfluid behaviour of a two-dimensional Bose gas*

Due to thermal fluctuations, two-dimensional (2D) systems cannot undergo a conventional phase transition associated to the breaking of a continuous symmetry. Nevertheless they may exhibit a phase transition to a state with quasi-long range order via the Berezinskii-Kosterlitz-Thouless (BKT) mechanism. A paradigm example is the 2D Bose fluid, such as a liquid helium film, which cannot condense at non-zero temperature although it becomes superfluid above a critical phase space density. The quasi-long range coherence and the microscopic nature of the BKT transition were recently explored with ultracold atomic gases. However, a direct observation of superfluidity in terms of frictionless flow was still missing for these systems. In this talk, I will report on recent measurements of the superfluidity of a 2D trapped Bose gas using a moving obstacle formed by a micron-sized laser beam. We find a dramatic variation of the response of the fluid, depending on its degree of degeneracy at the obstacle location.

R.A. Williams: *Synthetic gauge fields for ultracold atoms*

We report experimental work synthesizing gauge fields for ultracold atoms. I will first summarize earlier work from the NIST group, introducing how the technique of coupling internal states of an atom with "Raman" lasers generates synthetic scalar gauge fields and spin-orbit coupling [1]. I will describe how this laser dressing can lead to modified interactions between ultracold atoms [2]. I will also discuss how a combination of Raman coupling and radiofrequency fields can generate a one-dimensional lattice potential with a built-in artificial vector potential [3].

[1]Y.-J. Lin et al., Nature **471**, 83 (2011)
[2]R. A. Williams et al., Science **335**, 314 (2012)
[3]K. Jiménez-García et al., Phys. Rev. Lett. **108**, 225303 (2012)

P. Windpassinger: *Simulating classical magnetism and artificial gauge fields in optical lattices*

Ultracold bosons in optical lattices have during the past years been applied to emulate various solid state systems. The presentation will discuss the experimentally realized simulation of a frustrated classical spin system in a triangular optical lattice and the verification of the corresponding spin-phase diagram. Particular focus will be put on the frustrated regions of the phase diagram and the associated phase transitions.

The second part will be concerned with the recent realization of an artificial vector gauge field in a one dimensional optical lattice and the extensions to two dimensional systems.

As both findings rely on the application of an external periodic force, the main underlying technical method will also be discussed in detail.

W. Zwerger: *The unitary Fermi gas: a benchmark case for many-body physics*
