Research Frontiers in Ultracold Quantum Gases

685. WE-Heraeus-Seminar

December 17 - 21, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 685. WE-Heraeus-Seminar:

Since the first experimental realization of Bose-Einstein condensation in ultracold atomic gases in 1995, there have been several substantial breakthroughs. Today, systems of bosonic or fermionic quantum gases allow for a very high level of experimental control concerning all ingredients of the underlying many-body Hamiltonian. The corresponding trapping geometry can be designed to be harmonic, anharmonic or, recently, even box-like, which mimics a quasi-uniform potential. Furthermore, the shape of the two-particle interaction can be modified from the short-ranged and isotropic contact interaction to the long-ranged and anisotropic dipolar interaction. In particular the possibility to tune the strength of the contact interaction to basically any attractive or repulsive value with the aid of the Feshbach resonances allows nowadays to probe quantum fluids in regimes and under conditions hitherto unavailable. Since 2011 it has even been experimentally achieved to also tune the kinetic energy of the many-body Hamiltonian by producing synthetic spin-orbit coupling. This nourishes the prospect to generate for neutral atoms abelian gauge fields, as they appear in electromagnetism for charged particles, but also non-abelian gauge fields, as they occur in the standard model of elementary particle physics. Therefore, quantum gases are considered to be ideal quantum simulators, that is, they are best capable to simulate difficult quantum problems in condensed matter physics and other fields of physics in the sense of Richard Feynman from 1982.

Scientific Organizers:

PD Dr. Axel Pelster	Technische Universität Kaiserslautern, Germany E-mail: axel.pelster@physik.uni-kl.de
Prof. Carlos Sá de Melo	Georgia Institute of Technology, Atlanta, USA E-mail: carlos.sademelo@physics.gatech.edu

Program

Program

Sunday, December 16, 2018

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, December 17, 2018

07:30	*BREAKFAST*	
08:45 – 09:00	Carlos Sá de Melo	**Opening and Welcome**
Session 1:	**Photons**	
09:00 – 09:45	Martin Weitz	**Bose-Einstein condensation of photons and periodic potentials for light**
09:45 – 10:30	Michiel Wouters	**Quantum fluids of exciton-polariton**
10:30 – 11:00	*COFFEE BREAK*	
Session 2:	**Quantum Droplets**	
11:00 – 11:45	Tilman Pfau	**Dipolar quantum gases and liquids**
11:45 – 12:30	Leticia Tarruell	**Solitons and droplets in two-component Bose-Einstein condensates with tunable interactions**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:45	*LUNCH*	

Monday, December 17, 2018

Session 3:	**Long-Range Interactions**	
14:00 – 14:45	Giovanna Morigi	**Collective dynamics of atomic ensembles interacting via long-range forces**
14:45 – 15:30	Laurent Sanchez-Palencia	**Universal scaling laws for correlation spreading in long-range quantum systems**
15:30 – 16:00	*COFFEE BREAK*	
Session 4:	**Memorial**	
16:00 – 16:30	Carlos Sá de Melo	**Remembrances and Legacy of Debbie Jin**
16:30 – 17:30	**Plenary Poster Flash Presentations I**	
17:30 – 17:45	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
17:45 – 18:45	**Working Group Discussions I**	
18:45 – 20:15	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, free beverages)*	
20:15 – 22:00	***Poster Session I***	

Tuesday, December 18, 2018

08:00	*BREAKFAST*	
Session 5:	**Hybrid Systems**	
09:00 – 09:45	Arno Rauschenbeutel	**Observation of ultra-strong spin–motion coupling for cold atoms in optical microtraps**
09:45 – 10:30	Michael Thorwart	**Nonequilibrium quantum phase transitions in a hybrid atom-optomechanical system**
10:30 – 11:00	*COFFEE BREAK*	
Session 6:	**Cosmology**	
11:00 – 11:45	James Anglin	**Noise and turbulence in 2D sonic black holes**
11:45 – 12:30	Gretchen Campbell	**A supersonically expanding BEC: An expanding universe in the lab?**
12:30	*LUNCH*	

Tuesday, December 18, 2018

Session 7:	**Contributed Talks**	
14:00 – 14:30	Uwe Fischer	**Experimental quantum cosmology: Probing analogue trans-Planckian physics in dipolar Bose-Einstein condensates**
14:30 – 15:00	Philipp Preiss	**Quantum optics with massive particles**
15:00 – 15:30	Richard Schmidt	**Many-body physics with quantum impurities in cold atoms and beyond**
15:30 – 16:00	Julian Léonard	**Exploring quantum correlations in a many-body localized system**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:00	Emi Yukawa	**Nonholonomy of order parameters and su(3) vortices in spin-1 Bose-Einstein condensates**
17:00 – 17:30	Ednilson dos Santos	**Quantum turbulence in trapped atomic Bose–Einstein condensates**
17:30 – 18:30	**Plenary Poster Flash Presentations II**	
18:30 – 20:00	*DINNER*	
20:00 – 22:00	**Poster Session II**	

Wednesday, December 19, 2018

08:00	*BREAKFAST*	
Session 8:	**Many-Body Physics**	
09:00 – 09:45	Selim Jochim	**Probing many body physics in a 2D Fermi gas**
09:45 – 10:30	Carsten Robens	**Energy and short-range correlations of strong coupling Bose polarons**
10:30 – 11:00	*COFFEE BREAK*	
Session 9:	**Lattices**	
11:00 – 11:45	Johann Blatter	**Van der Waals type gas-liquid transition in the driven-dissipative Bose-Hubbard model**
11:45 – 12:30	Christian Gross	**From incommensurate magnetism to magnetic polarons in Fermi-Hubbard systems**
12:30	*LUNCH*	
14:00 – 18:30	**Excursion to the museum 'Haus der Geschichte', Bonn - Experience history –**	
18:30 – 20:00	*DINNER*	
Session 10:	**Evening Lecture**	
20:00 – 21:00	Wolfgang Ketterle	**How to dress RF photons with tunable momentum and magnetic spin-orbit coupling**

Thursday, December 20, 2018

08:00	*BREAKFAST*	
Session 11:	**Two-Electron Atoms**	
09:00 – 09:45	Leonardo Fallani	**Experiments with synthetic quantum systems of ultracold two-electron fermions**
09:45 – 10:30	Yoshiro Takahashi	**Quantum simulation using two-electron atoms in an optical lattice**
10:30 – 11:00	*COFFEE BREAK*	
Session 12:	**Complex Dynamics**	
11:00 – 11:45	Dieter Jaksch	**Dissipation induced non-stationary complex ultracold atom dynamics**
11:45 – 12:30	Masahito Ueda	**Dynamics of continuously monitored quantum many-body systems**
12:30	*LUNCH*	
Session 13:	**Dipolar Atoms and Molecules**	
14:00 – 14:45	Lauriane Chomaz	**Experiments on dipolar quantum gases of erbium atoms: roton mode in dipolar BECs and spin mixtures of dipolar fermions**
14:45 – 15:30	Silke Ospelkaus	**Preparing ultracold polar molecules**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 17:00	**Plenary Poster Flash Presentations III**	
17:00 – 18:30	**Working Group Discussions II**	
18:30 – 20:00	*DINNER*	
20:00 – 22:00	**Poster Session III**	

Friday, December 21, 2018

08:00	*BREAKFAST*	
Session 14:	**Solitons and Vortices**	
09:00 – 09:45	Joachim Brand	**Quantum dark solitons in 1D quantum gases**
09:45 – 10:30	Franco Dalfovo	**Vortex structure and dynamics in a temperature quenched BEC**
10:30 – 11:00	*COFFEE BREAK*	
Session 15:	**Spin Liquids**	
11:00 – 11:45	Anna Sanpera	**Signatures of quantum spin liquids in small lattices**
11:45 – 12:00	Axel Pelster	**Poster awards, summary and closing remarks**
12:00 – 13:30	*LUNCH*	

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Friday evening for participants leaving the next morning.*

Posters

Posters

P001	Bakhodir Abdullaev	**Collective modes of anyons in a 2D harmonic trap**
P002	Jesse Amato-Grill	**Interaction spectroscopy of a two-component Mott insulator**
P003	Antun Balaž	**Vortices and droplets in dipolar Bose-Einstein condensates**
P004	Luca Bayha	**Anomalous breaking of scale invariance in a two dimensional Fermi gas**
P005	Russel Bisset	**Extracting the roton-maxon spectrum in a dipolar condensate**
P006	Annabelle Bohrdt	**New probes of the t-J model in quantum gas microscopes**
P007	Abdelaali Boudjemaa	**Self-bound droplets in a dipolar Bose-Bose mixture**
P008	Georg Bruun	**Quantum dynamics, induced interactions, and pairing with the Bose polaron**
P009	BerisLav Buca	**Non-stationary coherent quantum many-body dynamics through dissipation**
P010	Thomas Busch	**Efficient quantum engines in iteracting ultracold gases**
P011	David Clément	**Probing the 3D superfluid-to-Mott crossover with metastable Helium atoms**
P012	Stefan Donsa	**Expanding Bose-Einstein condensate in disorder: Role of many-body interactions for Anderson localization**

P013	Ottó Elíasson	**Towards dispersive-probing enhanced measurement precision in quantum gas microscopes**
P014	Serena Fazzini	**Interaction induced fractionalization and topological superconductivity in the polar molecules anisotropic t-J model**
P015	Kai Frye	**Quantum optics on the International Space Station**
P016	Filippo Gaggioli	**Critical dynamics of photonic lattices in phase space**
P017	Albert Gallemí Camacho	**Collisions between quantum droplets**
P018	Yung Kwan Goddard Lee	**Non-Axisymmetric vortex equilibria in a Bose Einstein condensate**
P019	Sandro Gödtel	**Selfgravitating BEC in external gravity: Modifying the selfinteraction constant**
P020	Fabian Grusdt	**Meson gas theory of the t-J model**
P021	Nadia Guebli	**Quantum droplets in Bose-Bose mixture at finite temperature**
P022	Thomas Hartke	**Spin transport in a Mott Insulator of ultracold fermions**
P023	Bharath Hebbe Madhusudhana	**Singular loops and their non-Abelian geometric phases in spin-1 ultracold atoms**
P024	Ana Hudomal	**Transport in optical lattices with flux**
P025	Tobias Ilg	**Dimensional crossover for the beyond-mean-field correction in Bose gases**

Posters

P026	Bernhard Irsigler	**Transverse magnetization effect of the spin-imbalanced Hofstadter-Hubbard model**
P027	Jian Jiang	**Non-equilibrium dynamics of interacting Bosons in an optical lattice**
P028	Hans Keßler	**Towards a continuously operating matter wave interferometer for inertial sensing**
P029	Tom Kim	**Thermodynamics and structural transition of binary atomic Bose-Fermi mixtures in box or harmonic potentials: A path-integral study**
P030	Niels Kjaergaard	**Elucidating scattering resonances with an ultracold atom collider**
P031	Lauritz Klaus	**Towards the Bose Polaron in an ultracold Bose-Fermi mixture of ^{133}Cs and ^{6}Li**
P032	Joannis Koepsell	**Direct imaging of magnetic Hubbard polarons**
P033	Haggai Landa	**Singular Floquet scattering with atomic interactions**
P034	Tim Langen	**Towards direct laser cooling of barium monofluoride**
P035	Daniel Laukhardt	**Bose-Einstein condensates in toroidal guiding potentials for ATOMTRONICS devices**
P036	Niklas Mann	**Emerging quantum-many body effects in a hybrid atom-optomechanical system**
P037	Polina Matveeva	**Dimensional phase transition from 1D quantum liquids to 3D condensates**
P038	Azadeh Mazloom Shahraki	**Superfluidity in density imbalanced bilayers of dipolar fermions**

P039	Rob McDonald	**Derivation and application of stochastic Ehrenfest relations from the stochastic projected Gross-Pitaevskii equation**
P040	Matthias Meister	**The space atom laser: An isotropic source for ultra-cold atoms in microgravity**
P041	Yijian Meng	**Cold-atom-based implementation of the Dicke model in the ultra-strong coupling regime**
P042	Simeon Mistakidis	**Many-Body polaron dynamics**
P043	Natália Salomé Móller	**Weakly interacting Bose gas on a sphere**
P044	Paulsamy Muruganandam	**Ground state phases and excitation of Rashba spin-orbit coupled Bose-Einstein condensates with Rabi mixing in two-dimensions**
P045	Mehmet Oktel	**Temperature dependent density profiles and collective oscillations of dipolar droplets**
P046	Stefan Ostermann	**Cavity-induced emergent topological spin textures in a Bose-Einstein condensate**
P047	Nick P. Proukakis	**Dynamical equilibration and critical exponents in quenched quantum gases**
P048	Maximilian Prüfer	**Observation of universal dynamics in a spinor gas far from equilibrium**
P049	Milan Radonjic	**Out-of-equilibrium dynamics of ultracold bosons in time-dependent random potentials**
P050	Babu Mareeswaran Rajendran	**Non-autonomous bright Matter-Wave solitons in spin-2 Bose-Einstein condensates**

P051	Arko Roy	**Design and characterization of a quantum-gas heat pump**
P052	Alejandro Saenz	**Quantum tunneling showing its strength**
P053	Frederic Sauvage	**(Machine) learning to quickly swipe through a quantum phase transition**
P054	Peter Schlagheck	**Phase transition kinetics for a Bose Einstein condensate in a periodically driven band system**
P055	Manuel Schmitt	**Quantum droplets with tilted dipoles**
P056	Julius Seeger	**Experimental demonstration of Bose-Einstein condensation in the first excited band of the optical honeycomb lattice**
P057	Airlia Shaffer	**2d Fermi gases under the microscope**
P058	Boris Shteynas	**How to dress radio-frequency photons with tunable momentum**
P059	Angom Dilip Kumar Singh	**Quantum Hall states of 2D Bose-Hubbard model and disorder**
P060	Enrico Stein	**Material Mean-Field equations for photon Bose-Einstein condensates**
P061	Denis Vasilyev	**Quantum scanning microscope for cold atoms**
P062	Vladimir Veljić	**Stability diagram of degenerate Fermi gases of polar molecules with tilted dipoles**
P063	Artem Volosniev	**Effective approach to impurity dynamics in One-Dimensional trapped Bose gases**

P064	Etienne Wamba	**Mapping a slow evolution onto a periodic driving of a Bose gas in the mean-field regime**
P065	Nicola Wurz	**Coherent manipulation of spin correlations in the 2D Fermi Hubbard Model**
P066	Man Hon Yau	**Chern number spectrum of ultra-cold fermions in optical lattices as a function of independently tunable artificial magnetic, Zeeman and spin-orbit fields**
P067	Wei Zhang	**Quantum simulation in ultracold quantum gases of Alkaline-earth-like atoms**
P068	Junhui Zheng	**Measuring the topological phase transition via the single-particle density matrix**
P069	Nikolaj Thomas Zinner	**Realizing exotic quantum few-body states with strongly interacting systems in 1D**

Abstracts of Lectures

(in alphabetical order)

Noise and turbulence in 2D sonic black holes

James Anglin

Technische Universität Kaiserslautern
Kaiserslautern, Germany

Can we really make sonic black holes with quantum gases? Can we observe Hawking radiation in the lab?

The answers depend on how strictly we define these goals. Under sufficiently broad definitions, Jeff Steinhauer has already achieved both of them. Under stricter definitions, however, serious challenges remain.

In particular I will show that Unruh's famous spacetime analogy actually requires at least two spatial dimensions, and that finite ergoregions in more than one spatial dimension are all unstable to turbulence, which then also destroys the spacetime analogy. I will then explain why even this inherently self-limiting analogy with gravity may still be of great interest to quantum gravity theorists, and further argue that sonic horizons in quantum gases are of interest even beyond the strict gravitational analogy.

Van der Waals type gas—liquid transition in the driven-dissipative Bose-Hubbard model

M. Biondi, F. Gaggioli, S. Schmidt, and G. Blatter

Theoretical Physics, ETH Zürich, Switzerland
E-mail: blatterj@phys.ethz.ch

The Hubbard model in its fermionic and bosonic versions encompasses numerous solid state and quantum optical systems, e.g., Vanadium Oxide, Josephson junction arrays, or cold bosonic atoms in an optical lattice. Here, we focus on its photonic version in a cavity array that includes drive and dissipation and thus is naturally nonequilibrium in character. Starting out with the single nonlinear cavity, we discuss how its closeness to a bistability with dark (few photons) and bright (many photons) states lays the foundation for its complex steady states [1]. Employing a mean-field decoupling for the intercavity hopping J, we find [2] that the steep crossover between low and high photon-density states inherited from the single cavity transforms into a gas—liquid bistability at large cavity-coupling J. We formulate a van der Waals like gas—liquid phenomenology for this nonequilibrium setting and determine the relevant phase diagrams, including a new type of diagram where a lobe-shaped boundary, reminiscent of the Mott-Insulator lobes of the equilibrium Bose-Hubbard model, separates smooth crossovers from sharp, hysteretic transitions. Calculating quantum trajectories for a one-dimensional system, we provide insights into the microscopic origin of the bistability. Finally, we place these results into context with recent developments that demonstrate [3] the validity of simple mean-field theory in the limit of small interaction U and the equivalence of the driven nonequilibrium system with the equilibrium transition of a van der Waals/Ising system near the critical point [4,5].

References

[1] P.D. Drummond and D.F. Walls, J. Phys. A: Math. Gen. **13**, 725 (1980).
[2] M. Biondi, G. Blatter, H.E. Tureci, and S. Schmidt, Phys. Rev. A **96**, 043809 (2017).
[3] W. Casteels, R. Fazio, and C. Ciuti, Phys. Rev. A **95**, 012128 (2017).
[4] M. Foss-Feig, P. Niroula, J.T. Young, M. Hafezi, A.V. Gorshkov, R.M. Wilson, and M.F. Maghrebi, Phys. Rev. A **95**, 043826 (2017).
[5] F. Vicentini, F. Minganti, R. Rota, G. Orso, and C. Ciuti, Phys. Rev. A **97**, 013853 (2018).

Quantum dark solitons in 1D quantum gases

J. Brand[1,2] and S. S. Shamailov[1,2]

[1] Institute for Advanced Study, Massey University, Auckland, New Zealand
[2] Dodd-Walls Centre for Photonic and Quantum Technology, New Zealand

The abstract Dark and grey soliton-like states are shown to emerge from numerically constructed superpositions of translationally-invariant eigenstates of the interacting Bose gas in a toroidal trap. The exact quantum many-body dynamics reveals a density depression with superdiffusive spreading that is absent in the mean-field treatment of solitons. A simple theory based on finite-size bound states of holes with quantum-mechanical center-of-mass motion quantitatively explains the time-evolution of the superposition states and predicts quantum effects that could be observed in ultra-cold gas experiments. The soliton phase step is shown to be a key ingredient of an accurate finite size approximation, which enables us to compare the theory with numerical simulations. The fundamental soliton width, an invariant property of the quantum dark soliton, is shown to deviate from the Gross-Pitaevskii predictions in the interacting regime and vanishes in the Tonks-Girardeau limit.

In addition to the one-dimensional Bose gas in the Lieb-Liniger model [1], we also consider the one-dimensional Fermi gas with attractive delta-function interactions (Yang-Gaudin model) [2]. The corresponding Bethe-ansatz equations are solved for finite particle number and in the thermodynamic limit in order to obtain the *yrast* dispersion, i.e. the dispersion relation of the eigenstates of lowest energy for given momentum. Properties corresponding to the soliton-like nature of the yrast excitations are calculated including the missing particle number, phase step, and inertial and physical masses. The inertial to physical mass ratio, which is related to the frequency of oscillations in a trapped gas, is found to be unity in the limits of strong and weak attraction and fall to ≈0.78 in the crossover regime. This result is contrasted by one-dimensional mean field theory, which predicts a divergent mass ratio in the weakly attractive limit. By means of an exact mapping our results also predict the existence and properties of dark-soliton-like excitations in the super Tonks-Girardeau gas. The prospects for experimental observations are briefly discussed.

References

[1] Shamailov, S.S., Brand, J.: Quantum dark solitons in the one-dimensional Bose gas, arXiv:1805.07856 (2018).

[2] Shamailov, S.S., Brand, J.: Dark-soliton-like excitations in the Yang-Gaudin gas of attractively interacting fermions. New J. Phys. **18**, 075004 (2016).

A Supersonically expanding BEC: An expanding universe in the lab?

G.K. Campbell

Joint Quantum Institute, NIST and UMD College Park, U.S.A
E-mail: gcampbe1@jqi.umd.edu

The massive scale of the universe makes the experimental study of cosmological inflation difficult. This has led to an interest in developing analogous systems using table top experiments. In a recent experiment, we model the basic features of an expanding universe by drawing parallels with an expanding ring-shaped Bose Einstein Condensate (BEC).We study the dynamics of a supersonically expanding ring-shaped BEC both experimentally and theoretically. The ring-shaped BEC serves as the background vacuum and phonons are the analogue to photons in the expanding universe. The expansion redshifts long-wavelength excitations, as in an expanding universe. After expansion, energy in a radial mode excitation leads to the production of bulk topological excitations – solitons and vortices – driving the production of a large number of azimuthal phonons. These complex nonlinear dynamics, fueled by the energy stored coherently in one mode, are reminiscent of a type of “preheating” that may have taken place at the end of inflation.

Experiments on dipolar quantum gases of erbium atoms: roton mode in dipolar BECs and spin mixtures of dipolar fermions

L. Chomaz[1], D. Petter[1], G. Natale[1], A. Patscheider[1], S. Baier[1], M. J. Mark[1,2], F. Ferlaino[1,2]

[1] *Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria*

[2] *Institut für Quantenoptik und Quanteninformation, Osterreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria*

E-mail: lauriane.chomaz@uibk.ac.at

Ultracold gases of highly magnetic atoms offer an ideal platform for investigating many-body quantum phenomena in the presence of dipole-dipole interactions (DDI). In my talk, I will first report on our investigation of a roton mode on a dipolar BEC. The roton mode denotes an elementary excitation of minimal energy at finite momentum, similar to the case of superfluid helium He-II [1]. In contrast to the He-II's case, the roton mode in a dipolar BEC does not require strong interactions, but arises from the long-range and anisotropic nature of the DDI. First predicted in 2003 [2], it has long remained elusive to observation. In our experiment, we first observed the roton mode via the exponential growth of its population after quenching a BEC of ^{166}Er to instability [3]. More recently, we have also probed the roton softening of the excitation spectrum of a stable BEC, employing Bragg spectroscopy.

In a second time, I will present our realization of an effective spin-1/2 mixture of fermionic ^{167}Er in the quantum degenerate regime with tunable interactions. We performed a first study of the collisional behavior of the mixture, showing a remarkable stability in the strongly interacting regime, enhanced on the attractive side of the resonance [5]. This study paves the way to studying superfluid pairings of fermions in presence of an unprecedented few-body scattering scenario.

References

[1] L. D. Landau, The theory of superfluidity of helium II. *J. Phys. (Moscow)* **5**, *71* (1941).

[2] L. Santos, G.V. Shlyapnikov, and M. Lewenstein, Roton-maxon spectrum and stability of trapped dipolar Bose-Einstein condensates. *PRL* **90**, *250403* (2003)

[3] L. Chomaz, & al., Observation of roton mode population in a dipolar quantum gas. *Nature Physics*, **14** (5), p.442 (2018).

[4] S. Baier, & al., Realization of a strongly interacting fermi gas of dipolar atoms. *PRL* **121**, *093602* (2018).

Vortex structure and dynamics in a temperature quenched BEC

F. Dalfovo

INO-CNR BEC Center and
Dipartimento di Fisica, Università di Trento, Trento, Italy

In the recent years, several experiments have been performed at the BEC Center in Trento with the aim of better understanding the behavior of quantized vortices in a Bose-Einstein condensate of ultracold atoms. Vortices are spontaneously produced in temperature quenches across the BEC transition *via* the Kibble-Zurek mechanism [1,2]. Suitable imaging techniques are used to extract relevant information about the motion of individual vortex filaments in the condensate [3], as well as to observe the effects of their mutual interactions [4,5]. In this talk, I will briefly overview the most recent results of the group, together with the models and theories that we use to support the experimental observations. I will first present the case of vortex filaments which precess due to boundary effects in a manner analogous to that of a classical spinning top [6]. Then I will show how a quantized vortex filament can be imaged with enough accuracy to see its core structure down to the healing length scale [7]. Finally, I will discuss the results of extensive numerical simulations of the entire non-equilibrium process associated with a quench across the BEC phase transition and the subsequent post-quench dynamics, underlining the role of vortices in the condensate growth [8].

References

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[2] Donadello et al., Phys. Rev. Lett. **113**, 065302 (2014)
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Experiments with synthetic quantum systems of ultracold two-electron fermions

L. Fallani[1]

[1] *Department of Physics and Astronomy, University of Florence, Sesto Fiorentino, Italy*

I will report on recent experiments performed with ultracold quantum gases of two-electron ^{173}Yb fermions. Specifically, I will focus on the application of the ultranarrow optical "clock" transition connecting long-lived electronic states $^1S_0$ and $^3P_0$ for the realization of new synthetic quantum systems. Extending previous experimental work on the realization of "synthetic dimensions" [1], we have exploited the clock transition to demonstrate new schemes for spin-orbit coupling in pure two-level systems and the generation of tunable gauge fields in synthetic ladders [2]. I will describe the latest experimental developments and the new perspectives offered by the control of atom-atom interactions with orbital Feshbach resonances [3], that recently allowed the coherent production of weakly-bound $^{173}Yb_2$ ($^1S_0$ + $^3P_0$) molecules and the coherent control of their internal state [4].

References

[1] M. Mancini et al., Science **349**, 1510 (2015).
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From incommensurate magnetism to magnetic polarons in Fermi-Hubbard systems

C. Gross[1]

[1]Max-Planck-Institut für Quantenoptik, Garching, Germany

The Hubbard model offers an intriguing playground to explore strongly correlated many-body systems. Much of its complexity arises from the interplay of spin and charge degrees of freedom. Here we report on the experimental study of one- and two-dimensional synthetic Hubbard systems implemented on the optical lattice platform. We discuss the recent observation of incommensurate magnetism in one dimension and the imaging of magnetic polarons in two dimensions. Due to our spin and charge resolved imaging technique, our observations are independent of any presumed model. Future extensions of these experiments may allow one to study the interaction of polarons as a precursor to collective many body physics in the Hubbard model.

Dissipation induced non-stationary complex ultracold atom dynamics

B. Buca, J. Tindall, and D. Jaksch

[1]*Clarendon Laboratory, Parks Road, University of Oxford, Oxford OX1 3PU, UK*

The assumption that physical systems relax to a stationary state in the long-time limit underpins statistical physics and much of our intuitive understanding of scientific phenomena. For isolated systems, this follows from the eigenstate thermalization hypothesis. When an environment is present the expectation is that all of phase space is explored, eventually leading to stationarity.

In this talk, we will identify and discuss simple and generic conditions for dissipation to prevent a quantum many-body system from ever reaching a stationary state [1]. We go beyond dissipative quantum state engineering approaches towards controllable long-time non-stationary dynamics typically associated with macroscopic complex systems. The resulting coherent and oscillatory evolution constitutes a dissipative version of a quantum time-crystal.

We will show how such dissipative dynamics can be engineered and studied with fermionic ultracold atoms in optical lattices using current technology. We discuss how dissipation leads to long-range quantum coherence, complexity, and η-pairing indicating a superfluid state in these setups.

References

[1] B. Buca, J. Tindall, and D. Jaksch, *Complex coherent quantum many-body dynamics through dissipation*, arXiv:1804.06744 (2018).

Probing Many Body Physics in a 2D Fermi Gas

Selim Jochim

Physikalisches Institut, Heidelberg University, Germany

During the past years we have studied the BEC-BCS crossover using a variety of tools and observables. Observing the in-situ momentum distribution of the gas we could establish a phase diagram and the coherence of the system. Driving RF spin flip transitions we studied the pairing properties of the gas, in particular also in the normal regime at very high temperatures. Finally we study the dynamics of the gas by observing collective motion of the gas. In this way we observe an anomalous breaking of scale invariance. All the different methods find previously not understood behavior of the gas in the strongly interacting regime at $ln(k_F\, a) \approx +1$. New observables determining correlations between particles are needed to make a connection between all these observations. I will present first progress towards this goal.

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How to dress RF photons with tunable momentum and magnetic spin-orbit coupling

W. Ketterle

MIT, Cambridge, USA

The properties of ultracold atoms can be profoundly modified with the help of laser beams. They can couple spin and motion and turn a Bose-Einstein condensate into a supersolid. A powerful method is periodic modulation of potentials (Floquet engineering). I will illustrate this method by showing how a modulated magnetic field can dress radiofrequency photons with tunable momentum [1].

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Collective dynamics of atomic ensembles interacting via long-range forces

G. Morigi

[1]*Saarland University, Saarbrücken, Germany*

In this talk we will review recent work on the dynamics of ultracold atoms in optical resonators. The stationary phases of the atoms here emerge from the interplay between thermal and quantum fluctuations, the long-range interactions due to multple photon scattering, and quantum shot noise. This interplay can give rise to the spontaneous formation of spatial and temporal pattern. The dynamics, moreover, reveal the existence of prethermalized states which are expected to be stable over the experimental time scales. We present a theoretical analysis of this behaviour in the semiclassical and deep in the quantum limit, and discuss the role of quantum fluctuations on the stability of these spatio-temporal structures.

Preparing ultracold polar molecules

S. Ospelkaus

[1]IInstitut for Quantum Optics, Leibniz University Hannover, 30173 Hannover, Germany

E-mail: silke.ospelkaus@iqo.uni-hannover.de

Laser cooling and trapping of atoms have paved the way for revolutionary progress in atomic physics ranging from the development of precise atomic clocks to quantum simulation. The complex structure of molecules with additional quantum degrees of freedom such as vibration and rotation makes cooling of molecules to ultracold temperatures particularly challenging. However, it is the unique molecular structure that provides largely unexplored novel opportunities. These range from the control of ultracold chemical reactions and precision measurements to strongly correlated dipolar quantum many-body systems.

In my talk, I will discuss two different approaches towards the preparation of ultracold molecular ensembles: First, I will present a scheme for Zeeman slowing a large class of molecules to speeds trappable by magnetic or magneto-optical traps [1]. The scheme can be applied to molecular radicals emitted from a cryogenic buffer gas cells and should result in a increase in the molecule number trapped in molecular magneto-optical traps by several orders of magnitudes.

Finally, I will discuss our progress towards the preparation of quantum degenerate ensembles of $^{23}Na^{39}K$ molecules starting from ultracold atomic ensembles. I will report on magnetic Feshbach resonance loss spectroscopy in all possible combinations of hyperfine sub-levels with an ultracold atomic mixture of ^{23}Na and ^{39}K and the use of our results to refine potential energy curves for NaK molecules [3] and the preparation of dual-species quantum degenerate mixtures of bosonic ^{23}Na ^{39}K mixtures [2]. Finally, I will discuss our experiments on Feshbach molecule creation and two-photon spectroscopy of the ro-vibrational ground state.

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Dipolar quantum gases and liquids

T. Pfau[1]

[1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology (IQST),
Universität Stuttgart, Germany
E-mail: t.pfau@physik.uni-stuttgart.de

Dipolar interactions are fundamentally different from the usual van der Waals forces in real gases. Besides the anisotropy the dipolar interaction is nonlocal and as such allows for self organized structure formation. More than ten years ago the first dipolar effects in a quantum gas were observed in an ultracold Chromium gas. By the use of a Feshbach resonance a purely dipolar quantum gas was observed three years after [1]. Recently it became possible to study degenerate gases of lanthanide atoms among which one finds the most magnetic atoms. The recent observation of their collisional properties includes the emergence of quantum chaos and very broad resonances [2,3]. Also anisotropic superfluidity could be observed [10]. Similar to the Rosensweig instability in classical magnetic ferrofluids self-organized structure formation was expected. In our experiments with quantum gases of Dysprosium atoms we could recently observe the formation of a droplet crystal [4]. In contrast to theoretical mean field based predictions the super-fluid droplets did not collapse. We find that this unexpected stability is due to beyond meanfield quantum corrections of the Lee-Huang-Yang type [5,6]. We observe and study self-bound droplets [7] which can interfere with each other. We also observe self-organized stripes in a confined geometry [8] and collective scissors mode oscillations of dipolar droplets [9]. These droplets are 100 million times less dense than liquid helium droplets and open new perspectives as a truly isolated quantum system.

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Observation of ultra-strong spin–motion coupling for cold atoms in optical microtraps

A. Dareau,[1] Y. Meng,[1] P. Schneeweiss,[1] and A. Rauschenbeutel[1,2]

[1] *Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria*
[2] *Department of Physics, Humboldt-Universität zu Berlin, 10099 Berlin, Germany*

We realize a mechanical analogue of the Dicke model, achieved by coupling the spin of individual neutral atoms to their quantized motion in an optical trapping potential. The atomic spin states play the role of the electronic states of the atomic ensemble considered in the Dicke model, and the in-trap motional states of the atoms correspond to the states of the electromagnetic field mode. The coupling between spin and motion is induced by an inherent polarization gradient of the trapping light fields, which leads to a spatially varying vector light shift. We experimentally show that our system reaches the ultra-strong coupling regime, i.e., we obtain a coupling strength which is a significant fraction of the trap frequency. Moreover, with the help of an additional light field, we demonstrate in-situ tuning of the coupling strength. Beyond its fundamental interest, the demonstrated one-to-one mapping between the physics of optically trapped cold atoms and the Dicke model paves the way for implementing protocols and applications that exploit extreme coupling strengths.

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Energy and short-range correlations of strong coupling Bose polarons

Carsten Robens, Zoe Yan, Yiqi Ni and Martin Zwierlein

Massachusetts Institute of Technology, Cambridge, USA
E-mail: CRobens@MIT.edu

The concept of the Bose polaron quasiparticle – a paradigm in modern solid-state physics – originates in Landau's idea of an electron forming its own attractive potential through the interaction with an ionic crystal lattice [1]. Inspired by this idea, Pekar developed a theory for strong interactions where the electron becomes dressed by crystal phonons thereby forming the Bose polaron quasiparticle whose properties can be vastly different from those of the bare electron [2]. The polaron concept has since been applied to describe a variety of physical phenomena including the colossal magnetoresistance in manganites, Helium-3 impurities in liquid Helium-4, metal oxide semiconductors, and high-T_C cuprates. Despite its conceptual simplicity, at strong interaction strength the Bose polaron poses remarkable challenges for both theoretical and experimental physicists due to a multitude of Bosons that simultaneously interact with the impurity thereby creating a complicated many-body state [3,4]. We here report on the first creation of an ensemble of Bose polarons – comprised of fermionic ^{40}K impurities immersed in a ^{23}Na a Bose Einstein condensate – in local equilibrium and in the strongly interacting regime. Using radio frequency ejection spectroscopy, we measure the Bose polaron ground-state energy and short-range correlations as a function of temperature across a variety of interaction strengths by tuning an interspecies magnetic Feshbach resonance.

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Remembrances and Legacy of Debbie Jin

C. A. R. Sá de Melo

Georgia Institute of Technology, Atlanta, USA

Recollections of a few personal memories and a discussion of the scientific legacy of Debbie Jin will be presented. Two areas of her experimental work that left a long lasting impact in Physics will be reviewed. The first topic covers her investigations of the crossover from BCS to BEC superfluidity, and the second subject encompasses her studies of ultra-cold dipolar molecules. She was a great physicist and a wonderful human being. It is a pity that she is no longer with us to discuss the latest advances in the field of ultra-cold atoms and molecules, but her pioneering work continues to be an inspiration for many new developments.

Universal Scaling Laws for Correlation Spreading in Long-Range Quantum Systems

L. Sanchez-Palencia[1]

[1] *Center for Theoretical Physics, Ecole Polytechnique, CNRS, Université Paris-Saclay, Route de Saclay, 91128 Palaiseau, France*
E-mail: lsp@cpht.polytechnique.fr

We review our recent work on the spreading of information in out-of-equilibrium quantum systems. For short range interactions, the propagation of any quantum signal is bounded by the so-called Lieb-Robinson bound. It creates a causality cone, inside which correlations show up. Conversely, they are exponentially suppressed outside the cone. which is ballistic for short range interactions and super-ballistic for long-range interactions. Extended bounds have been proposed systems with long range correlations. Recently, bounded propagation of correlations has been reported for ultracold atomic gases in optical lattices and quantum simulators of lattice spin systems based on artificial ion traps. The latter show significant deviations from expectations based on the Lieb-Robinson bounds.

Here we show that the causality cone features a double structure whose scaling laws can be related to a set of universal microscopic exponents that we determine. When the system supports excitations with a bounded group velocity, we find that the correlation edge moves ballistically, with a velocity equal to twice the maximum group velocity, while the dominant correlation maxima propagate with a different velocity that we derive. When the maximum group velocity diverges, as realizable with long-range interactions, we show that the correlation edge has a slower-than-ballistic motion. The motion of the maxima is, instead faster-than-ballistic for gapless systems, and ballistic for gapped systems. Our results have fundamental consequences on the spreading of information in correlated quantum systems and shed new light on existing experimental and numerical observations, for which our analysis provides a unified picture.

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Signatures of quantum spin liquids in small lattices

A. Yuste[1] and A. Sanpera[2,1]

[1]Depart. Physics. Universitat Autònoma Barcelona, Spain[2] ICREA, Institute Catalan of Advanced Research, 08011 Barcelona, Spain

Quantum spin liquids remain one of the most challenging subjects of quantum magnetism. Characterized by massive degenerate ground states that have long range entanglement and are locally indistinguishable, highly demanding numerical techniques are often needed to describe them. Here we propose an easy computational method based on exact diagonalization with
engineered boundary conditions to unveil \blue{some of} their most significant features in small lattices.
We derive the quantum phase diagram of diverse antiferromagnetic Heisenberg models in the triangular lattice. For all studied cases, our results are in accordance with the previous results obtained by means of sophisticated variational methods.

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Quantum simulation using two-electron atoms in an optical lattice

Y. Takahashi[1]

[1]Kyoto University, Kyoto, Japan

A system of ultracold atoms in an optical lattice is an ideal quantum simulator of a strongly correlated quantum many-body system due to the high controllability of system parameters. In this talk, I will report our recent experiments using ultracold fermions of ytterbium (Yb) in an optical lattice.

One of the unique properties of Fermi gases of two-electron atoms is a high spin symmetry of SU(N=2I+1) of nuclear spin I, which will show novel quantum magnetism. By using a ^{173}Yb Fermi gas with SU(N$\leq$ 6) symmetry, we develop a technique for optically inducing a nuclear spin singlet-triplet oscillation with a spin-dependent potential gradient for measuring nearest-neighbor anti-ferromagnetic spin correlations.

First, the straightforward comparison between the cases of SU(2) and SU(4) loaded in an optical dimerized lattice reveals the enhanced antiferromagnetic correlation for the SU(4) spin system compared with SU(2) as a consequence of a Pomeranchuk cooling effect [1]. In addition, we successfully observe the formation of nearest-neighbor antiferromagnetic spin correlations for SU(6) Fermi gases in 1D , 2D , and 3D optical lattices as well as a dimerized lattice. This work is an important step towards the observation of novel SU(N) quantum magnetism.

Other researches using Yb Fermi gases such as the experiments towards the quantum simulation of the Kondo effect will be also reported [2].

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Solitons and droplets in two-component Bose-Einstein condensates with tunable interactions

C. R. Cabrera, J. Sanz, A. Frölian, C. Chisholm, P. Thomas, B. Naylor, L. Tanzi, P. Cheiney and L. Tarruell[1]

ICFO-The Institute of Photonic Sciences, Castelldefels (Barcelona), Spain
E-mail: leticia.tarruell@icfo.es

Self-bound states appear in contexts as diverse as solitary waves in channels, optical solitons in non-linear media and liquid droplets. Their binding results from a balance between attractive forces, which tend to make the system collapse, and repulsive ones, which stabilize it to a finite size. In my talk, I will present experiments on various self-bound states possible in two-component Bose-Einstein condensates with tunable interactions.

First, I will discuss the stabilization of dilute quantum liquid droplets: macroscopic clusters of ultra-cold atoms that are eight orders of magnitude more dilute than liquid Helium, but have similar liquid-like properties. In particular, they remain self-trapped in the absence of external confinement due to the compensation of attractive mean-field forces and an effective repulsion stemming from quantum fluctuations [1]. We observe these self-bound droplets in a mixture of two Bose-Einstein condensates and, exploiting in situ imaging, we directly measure their ultra-low densities and micro-meter scaled sizes. We also observe that for small atom numbers quantum pressure is sufficient to dissociate the droplets and drive a liquid-to-gas transition, which we map out as a function of atom number and interaction strength [2].

In a second series of experiments, we study the difference existing between these liquid droplets and two-component bright solitons. In analogy to non-linear optics, the former can be seen as one-dimensional matter-wave solitons stabilized by dispersion, whereas the latter correspond to high-dimensional solitons stabilized by a higher order non-linearity due to quantum fluctuations. We find that depending on the system parameters, solitons and droplets can be smoothly connected or remain distinct states coexisting only in a bi-stable region [3].

Finally, we explore the scattering properties of a coherent superposition of two Bose-Einstein condensates with very unequal interactions. By adjusting the composition of the system, we observe as well the formation of self-bound states in this system, and study their properties.

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Nonequilibrium quantum phase transitions in a hybrid atom-optomechanical system

N. Mann[1], M. Reza Bakhtiari[1], A. Pelster[2], and M. Thorwart[1]

[1] *I. Institut für Theoretische Physik, Universität Hamburg, Jungiusstraße 9, 20355 Hamburg, Germany*

[2] *Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Erwin-Schrödinger Straße 46, 67663 Kaiserslautern, Germany*

We consider a hybrid quantum many-body system formed by a vibrational mode of a nanomembrane, which interacts optomechanically with light in a cavity, and an ultracold atom gas in the optical lattice of the out-coupled light [1]. The adiabatic elimination of the light field yields an effective Hamiltonian which reveals a competition between the force localizing the motional degree of freedom of the atoms and the membrane displacement. At a critical atom-membrane interaction, we find a nonequilibrium quantum phase transition from a localized symmetric state of the atom cloud to a shifted symmetry-broken state, the energy of the lowest collective excitation vanishes, and a strong atom-membrane entanglement arises. The effect occurs when the atoms and the membrane are non-resonantly coupled.
In addition, also the internal degrees of freedom of the atoms can be addressed [2]. We show that the hybrid atom-optomechanical system not only undergoes a nonequilibrium quantum phase transition between phases of different collective behavior, but also that the order of the phase transition can be tuned. Mediated by the light field of a common laser, the coupling between atoms and membrane is tuned by changing the laser intensity. Below a certain critical coupling, all the atoms occupy the energetically lower internal state and at the critical point, a nonequilibrium quantum phase transition happens. The order of the phase transition is influenced by the imbalance of the population of internal states and the transition frequency. For an asymmetric coupling, an asymmetric first order phase transition occurs with a preferred polarization orientation, while for the symmetric case, the phase transition is continuous for transition frequencies below a certain critical value and discontinuous above. Moreover, a hysteresis is obtained by adiabatically tuning the coupling strength in the regime of a first order phase transition.

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Dynamics of continuously monitored many-body systems

M. Ueda[1,2]

[1]*Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2] *RIKEN CEMS, Wako, Saitama 351-0198, Japan*

Quantum gas microscopy has revolutionalized our approach to quantum many-body systems where atoms trapped in an optical lattice can be observed in real time at the single-particle level. At such extreme precision, the measurement backaction due to Heisenberg's uncertainty relation can no longer be ignored. One should naturally be led to the question of whether or not many-body dynamics will be modified and, if so, in what way. We will address this issue by focusing on few-body dynamics and quantum critical phenomena. In the former, the measurement distinguishablity of multiple particles leads to a complete suppression of relative positional decoherence and quantum correlations persist under continuous observation in a manner analogous to decoherence-free subspace [1]. In the latter, the measurement backaction is shown to shift the quantum critical point and yield a unique critical phase beyond the scope of the standard universality class [2]. We also find that the propagation of correlations can exceed the Lieb-Robinson bound under such continuous observation [3]. Continuous observation also restricts the Hilbert space and the emergent nontrivial Berry phase yields some startling effects such as the Zeno Hall effect and retroreflection [4].

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Bose-Einstein Condensation of Photons and Periodic Potentials for Light

Martin Weitz

Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, 53115 Bonn, Germany

Cold atoms in lattice potentials are an attractive platform to simulate phenomena known from solid state theory, as the Mott-insulator transition. In contrast, the field of photonics usually deals with non-equilibrium physics. Recent advances towards photonic simulators of solid state equilibrium effects include polariton double-site and lattice experiments, as well as the demonstration of photon condensates in dye-filled microcavities. Here we report the creation of variable micropotentials for light within an ultrahigh-reflectivity mirror dye microcavity that is compatible with photon gas thermalization [1,2]. By repeated absorption-emission cycles on the dye molecules the photon gas thermalizes to the temperature of the dye solution, and in a single microsite we observe a photon Bose-Einstein microcondensate with a critical photon number of 68. Effective interactions between the otherwise nearly non-interacting photons are observed due to thermo-optic effects, and in a double-well system tunnel coupling between sites is demonstrated, as well as the hybridization of eigenstates. Prospects of the findings include photonic lattices in which cooling alone can produce entangled manybody states.

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Abstracts of Contributed Talks

(in alphabetical order)

Quantum turbulence in trapped atomic Bose-Einstein condensates

F. E. A. dos Santos[1]

[1]*Department of Physics, Federal University of São Carlos, São Carlos, Brazil*

The notion of turbulence in the quantum world was conceived long ago by Onsager and Feynman, but the occurrence of turbulence in ultracold gases has been studied in the laboratory only very recently. Albeit new as a field, it already offers new paths and perspectives on the problem of turbulence. Here the general properties of quantum gases at ultralow temperatures are considered, paying particular attention to vortices, their dynamics and turbulent behavior. Also a discussion on recent theoretical and experimental advances is made.

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Experimental Quantum Cosmology: Probing Analogue TransPlanckian Physics in Dipolar Bose-Einstein Condensates

Uwe R. Fischer

1. We consider an analogue de Sitter cosmos in an expanding quasi-two-dimensional Bose-Einstein condensate with dominant dipole-dipole interactions between the atoms or molecules in the ultracold gas. It is demonstrated that a hallmark signature of inflationary cosmology, the scale invariance of the power spectrum of inflaton field correlations, experiences strong modifications when, at the initial stage of expansion, the excitation spectrum displays a roton minimum. Dipolar quantum gases thus furnish a viable laboratory tool to experimentally investigate, with well-defined and controllable initial conditions, whether primordial oscillation spectra deviating from Lorentz invariance at trans-Planckian momenta violate standard predictions of inflationary cosmology.
2. A rapid quench in the dipolar gas, performed on the speed of sound of excitations propagating on the condensate background, leads to the dynamical Casimir effect (and hence analogue cosmological particle production), which can be characterized by measuring the density-density correlation function. It is shown, for both zero and finite initial temperatures, that the continuous-variable bipartite quantum state of the created quasiparticle pairs with opposite momenta, resulting from the quench, displays an enhanced potential for the presence of entanglement (represented by nonseparable and steerable quasiparticle states), when compared to a gas with solely repulsive contact interactions. Steerable quasiparticle pairs contain momenta from close to the roton, and hence quantum correlations significantly increase in the presence of a deep roton minimum.

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Exploring quantum correlations in a many-body localized system

J. Léonard, A. Lukin, M. Rispoli, R. Schittko, S. Kim, and M. Greiner

Harvard University, Cambridge, MA, USA

An interacting quantum system that is subject to disorder may cease to thermalize due to localization of its constituents, thereby marking the breakdown of thermodynamics. We realize such a many-body-localized system in a disordered Bose-Hubbard chain and characterize its entanglement properties through particle fluctuations and correlations.

We observe that the particles become localized, suppressing transport and preventing the thermalization of subsystems. Notably, we measure the development of non-local correlations, whose evolution is consistent with a logarithmic growth of entanglement entropy - the hallmark of many-body localization [1]. These results experimentally establish many-body localization as a qualitatively distinct phenomenon from localization in non-interacting, disordered systems.

Furthermore, we study the critical properties of the many-body localization transition. We identify a spatially separated, sparse-resonant structure of the system, which emerges at intermediate disorder strength and drives sub-diffusive particle motion. This sparse structure persists into non-factorizable higher-order correlation functions, thereby identifying the many-body nature of the critical regime.

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Quantum Optics with Massive Particles

Philipp Preiss[1]

[1]*Heidelberg University, Heidelberg, Germany*

Sources of entangled particle pairs are the backbone of modern quantum optics. They provide the basis both for fundamental studies of quantum statistics and entanglement, as well as for technological applications in quantum information.

In this talk, I will show how to realize entangled-pair sources of ultracold massive particles. Using optical tweezers, we implement deterministic sources of fermionic lithium atoms in a setting where spins and momenta of individual particles can be detected via fee-space fluorescence imaging.
We verify the indistinguishability of the particles through Hanbury Brown-Twiss experiments, in which we detect high-contrast second-order interference and strong correlations at third order. Switching on interactions between the particles, we obtain maximally entangled pairs, which we characterize through state tomography. These states are used as inputs for a Bell test, in which we verify Bell correlations in the motional degrees of freedom of massive particles.

In the future, our techniques will be used to measure coherence properties and order parameters of fermionic superfluids.

Many-body physics with quantum impurities in cold atoms and beyond

Richard Schmidt[1]

[1]*Max-Planck Institute of Quantum Optics, Hans-Kopfermann-Str. 1, 85748 Garching, Germany*

When an impurity is immersed into an environment, it changes its properties due to its interactions with the surrounding medium. The impurity is dressed by many-body excitations and forms a quasiparticle, the polaron. Depending on the character of the environment and the form of interactions, different types of polarons are created. In this talk, I will review recent experimental and theoretical progress on studying the many-body physics of polarons in ultracold atomic systems [1], and related polaronic phenomena encountered in two-dimensional semiconductors [2,3]. In the second part of the talk I focus on impurities interacting with bosonic quantum gases. Specifically, I discuss recent progress on the theoretical description of Rydberg excitations coupled to Bose-Einstein condensates. In such systems the interaction between the Rydberg atom and the Bose gas is mediated by the Rydberg electron. This gives rise to a new polaronic dressing mechanisms, where instead of collective excitations, molecules of gigantic size dress the Rydberg impurity. We develop a functional determinant approach [4] to describe the dynamics of such Rydberg systems which incorporates atomic and many-body theory. Using this approach, that we recently extended to fermionic systems [5], we predict the appearance of a superpolaronic state which has recently been observed in experiments [6,7].

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Nonholonomy of order parameters and su(3) vortices in spin-1 Bose-Einstein condensates

E. Yukawa[1] and M. Ueda[2,1]

[1]Center for Emergent Matter Science, RIKEN, 2-1, Hirosawa, Wako-shi, Saitama,Japan

[2] Department of Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan

In a superfluid with internal degrees of freedom, the superfluid vorticity exhibits a nonholonomic nature depending on the spin and/or multipolar texture. We derive a generalized Mermin-Ho relation that is applicable to a spin-1 Bose-Einstein condensate (BEC) regardless of its quantum phase. We show that the obtained Mermin-Ho relation, which can be expressed in terms of the Gell-Mann matrices and their structure factors, reveals the nonholonomic nature of vortices in spin-1 BECs [1]. This implies that there exist vortices dual to the spin vortices [2,3] (see Figure). These vortices belong to the other su(2) subalgebra of the su(3) algebra rather than the ordinary so(3) algebra formed by the spin vector. The generators of the su(2) subalgebra correspond to three physical quantities involving one spin-vector component and two quadrupolar-tensor components and have the structure factor of 2, which determines the quantized numbers of the rotations of the superfluid currents.

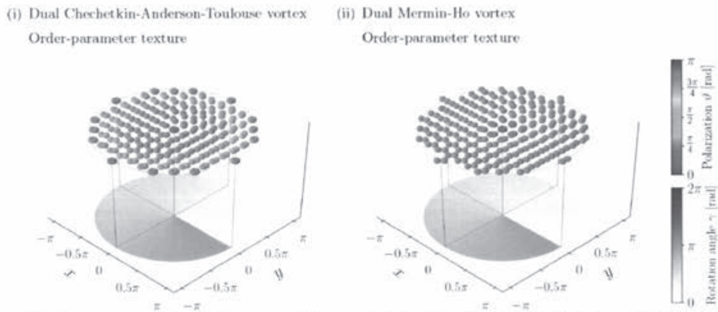

Figure. Order-parameter textures of the quantized vortices dual to the Chechetkin-Anderson-Toulouse vortex and the Mermin-Ho vortex. The color of the spherical plot of the order parameter corresponds to the polarization and the color of the projected circle indicates the orientation of the principal axe of the order parameter.

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Abstracts of Posters

(in alphabetical order)

Collective Modes of Anyons in a 2D Harmonic Trap

B. Abdullaev[1], **A.H. Ortikov[1]**, **and A. Pelster[2]**

[1] *National University of Uzbekistan, Tashkent, Uzbekistan*
[2] *Research Center OPTIMAS and Department of Physics, Technische Universität Kaiserslautern, Germany*

Based on Refs. [1,2] we work out a time-dependent variational approach for determining the low-lying collective modes of anyons confined in a 2D harmonic trap at zero temperature. At first, we discuss how their equilibrium properties as, for instance the ground-state energy, depend on the statistical interaction as well as on the trap aspect ratio. Afterwards, we investigate correspondingly the frequencies of the monopole, the quadrupole, and the Kohn mode.

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Interaction Spectroscopy of a Two-Component Mott Insulator

Jesse Amato-Grill[1,2], **Ivana Dimitrova**[1], **Niklas Jepsen**[1], **William Lunden**[1], **and Wolfgang Ketterle**[1]

[1] *MIT, Cambridge, MA, USA*
[2] *Harvard University, Cambridge, MA, USA*

We prepare and study a two-component Mott insulator of bosonic atoms with two particles per site. The mapping of this system to a magnetic spin model, and the subsequent study of its quantum phases, require a detailed knowledge of the interaction strengths of the two components. In this work, we use radio frequency (RF) transitions and an on-site interaction blockade for precise, empirical determination of the interaction strengths of different combinations of hyperfine states on a single lattice site. We create a map of the interactions of the lowest two hyperfine states of ^7Li as a function of magnetic field, including measurements of several Feshbach resonances with unprecedented sensitivity, and we identify promising regions for the realization of magnetic spin models.

Vortices and droplets in dipolar Bose-Einstein condensates

Antun Balaž[1] **and Axel Pelster**[2]

[1]Scientific Computing Laboratory, Center for the Study of Complex Systems, Institute of Physics Belgrade, University of Belgrade, Serbia
[2]Physics Department and Research center OPTIMAS, Technical University of Kaiserslautern, Germany
E-mail: antun.balaz@ipb.ac.rs

In the recent experiment [1], the Rosensweig instability was observed in a quantum ferrofluid of a strongly dipolar BEC, leading to a formation of atomic droplets, which represent a new state of quantum matter. In Ref. [2-4] it was demonstrated that the stability of such droplets is due to a quantum fluctuation correction of the ground-state energy [5-7]. Here we extend this previous theoretical description and develop a full Bogoliubov-Popov theory, which also takes into account the condensate depletion due to quantum fluctuations. We apply this approach and use extensive numerical simulations to study both the formation and the properties of vortices in a rotating ^{164}Dy BEC, including the droplet phase.

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Anomalous breaking of scale invariance in a two dimensional Fermi gas

L. Bayha[1], M. Holten[1], P.M. Muthy[1], N. Defenu[2], A.C. Klein[1], P.M.Preiss[1], T. Enss[2] and S. Jochim[1]

[1]Physics Institute, Heidelberg University, 69120 Heidelberg, Germany
[2] Institute for Theoretical Physics, Heidelberg University, 69120 Heidelberg, Germany

Symmetries of the Hamiltonian allow to predict the behavior of complicated physical systems, without knowing all microscopic details. But even if a classical Hamiltonian obeys a certain symmetry it is not guaranteed, that the symmetry also holds in the quantized theory. Such violations are called quantum anomalies and can appear in quantum field theories when a cut-off has to be introduced to regularize divergent quantities.

On this poster we present a striking manifestation of such a quantum anomaly in the breathing mode of an ultracold two dimensional Fermi gas. The classical two-dimensional Fermi gas with contact interactions is scale invariant, which fixes the frequency of the breathing mode in a harmonic trap. On the quantum mechanical level this scale invariance is broken by introducing the two dimensional scattering length, when regularizing the contact interactions. This results in a shift of the breathing mode frequency. In our experiments with a two component Fermi gas we observe significant shifts away from the scale invariant result that depend strongly on both interactions and temperature [1].

We found a further manifestation of this breaking of scale invariance in the coherence properties of the superfluid sample during the breathing cycle. Whereas the atom distribution shows a self-similar evolution in the weakly interacting regime we observe a significant violation of the scale invariant prediction in the strongly interacting regime [2]. Here the momentum distribution shows a strong deviation from the scale invariant expectation. In this regime the quantum anomaly strongly modifies the long range coherence properties of the system.

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Extracting the roton-maxon spectrum in a dipolar condensate

R. N. Bisset[1,2], P. B. Blakie[3] and S. Stringari[2]

[1] *Institut für Theoretische Physik, Leibniz Universität Hannover, Germany*
[2] *INO-CNR BEC Center, University of Trento, Italy*
[3] *University of Otago, Dunedin, New Zealand*

In recent years there has been considerable progress with the creation of Bose-Einstein condensates (BECs) of highly magnetic atoms such as chromium [1,2], erbium [3] and dysprosium [4]. One of the most intriguing possibilities for these dipolar condensates is the prediction of a roton-maxon dispersion relation for a BEC that is still weakly-interacting [5]. A roton population was recently observed experimentally for the first time during the dynamic collapse of the condensate after a quench of the interaction strength [6]. To gain a better picture, we develop an approach based on sum-rule theory, to experimentally extract the roton-maxon dispersion relation using a static optical perturbation.

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New probes of the t-J model in quantum gas microscopes

Annabelle Bohrdt[1,2], Christie S. Chiu[2], Geoffrey Ji[2], Muqing Xu[2], Daniel Greif[2], Markus Greiner[2], Eugene Demler[2], Fabian Grusdt[1,2] and Michael Knap[1]

[1]*Department of Physics and Institute for Advanced Study, Technical University of Munich, 85748 Garching, Germany*

[2]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

Ultracold atoms in optical lattices simulate complex many-body systems with a high degree of control and tunability. One exceptional feature of quantum gas microscopes in particular is that they enable repeated projective measurements of the many-body density matrix with single site resolution, thus providing large amounts of data. In this work, we use machine learning techniques to analyze such data snapshot-by-snapshot. This approach considers all available information without a potential bias towards one particular theory by the choice of an observable and can therefore select the theory which is more predictive in general. Specifically, we compare the data from an experimental realization of the two-dimensional Fermi-Hubbard model to two theoretical approaches: the geometric string theory, describing a state with hidden anti-ferromagnetic order, and a doped quantum spin liquid state of resonating valence bond type. Our machine learning analysis shows that the experimental data is better captured by the geometric string theory than the considered quantum spin liquid up to intermediate doping values. We furthermore analyze the decrease of the anti-ferromagnetic correlation length with increasing doping and temperature and detect signatures of a qualitative change in the structure of the data when the temperature approximately equals the spin-exchange energy. Our results demonstrate that machine learning opens new routes for analyzing the wealth of data generated by quantum gas microscopes in an unbiased and predictive manner.

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Self-bound droplets in a dipolar Bose-Bose mixture.

Abdelaali Boudjemaa

Department of Physics, Faculty of Exact Sciences and Informatics,
and Laboratory of Mechanics and Energy, Hassiba Benbouali University of Chlef,
P.O. Box 78, 02000, Ouled-Fares, Chlef, Algeria.

We study the properties of three-dimensional self-bound droplets in a dipolar Bose-Bose mixture at low temperatures. Effects of interaction on the stability, density profiles, and the size of the self-bound droplet are analyzed. The finite-temperature behavior of the droplet is also discussed.

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Quantum dynamics, induced interactions, and pairing with the Bose polaron

A. Camacho-Guardian, L. A. Peña Ardila, K. Knakkergaard Nielsen, T. Pohl, and G. M. Bruun

Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark

The Bose polaron is a versatile playground for exploring a range of fundamental topics in many-body physics. Here, we demonstrate how Landau's quasiparticle theory and in particular the concept of effective quasiparticle interactions can be systematically studied using the Bose polaron. Then we show how this effective interaction can lead to the formation of bound states of two polarons – the so-called bi-polaron. Finally, we discuss how quantum non-equilibrium dynamics can be probed by measuring the formation time of the Bose-polaron.

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Non-stationary coherent quantum many-body dynamics through dissipation

B. Buca[1], J. Tindall[1], and D. Jaksch[1,2]

[1]Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

[2] Centre for Quantum Technologies, National University of Singapore, 117543 Singapore

The assumption that quantum systems relax to a stationary state in the long-time limit underpins statistical physics and much of our intuitive understanding of scientific phenomena. For isolated systems this follows from the eigenstate thermalization hypothesis. When an environment is present the expectation is that all of phase space is explored, eventually leading to stationarity. Notable exceptions are decoherence-free subspaces that have important implications for quantum technologies and have so far only been studied for systems with a few degrees of freedom. Here we identify simple and generic conditions for dissipation to prevent a quantum many-body system from ever reaching a stationary state. We go beyond dissipative quantum state engineering approaches towards controllable long-time non-stationarity typically associated with macroscopic complex systems. This coherent and oscillatory evolution constitutes a dissipative version of a quantum time-crystal. We discuss the possibility of engineering such complex dynamics with fermionic ultracold atoms in optical lattices.

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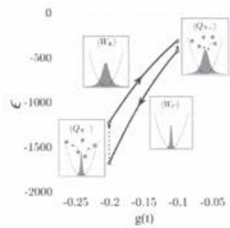
Efficient Quantum Engines in Interacting Ultracold Gases

Jing Li[1], Thomás Fogarty[1], Steve Campbell[2], and Thomas Busch[1]

[1]OIST Graduate University, 904-0495 Okinawa, Japan
[2]Dipartimento di Fisica, Università degli Studi di Milano, 20133 Milan, Italy



We present an investigation into thermodynamic cycles in ultracold atoms when the interactions between the atoms plays in important role. The first example uses a Bose–Einstein condensate with nonlinear interactions as the working medium and exploits a Feshbach resonance to change the interaction strength of the BEC. This allows to produce work by expanding and compressing the gas, and the power-output can be optimised using a shortcut-to-adiabticity [1].

The second example investigates the operation of a quantum Otto cycle near a quantum critical point. Specifically, we look at the pinning transition of a Tonks-Girardeau gas, when particles will become pinned at the minima of an optical lattice if they are commensurate with the number of lattice sites. Due to the energy gap opened at the pinning transition this provides a performance boost to the many-body system over a comparable ensemble of single particle engines.

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Probing the 3D superfluid-to-Mott crossover with metastable Helium atoms

C. Carcy[1] , H. Cayla[1] , A. Tenart[1] , M. Mancini[1] and D. Clément[1]

[1]Institut d'Optique Graduate School, France

We report on the momentum-space investigation of the three-dimensional (3D) superfluid-to-Mott crossover with a gas of metastable Helium-4 atoms. Momentum distributions are monitored in the far-field regime of expansion and with unprecedented resolution thanks to a single-atom-resolved detection method in 3D. We measure the condensed fraction to locate the Mott transition, finding a critical value matching quantum Monte-Carlo calculations, distinctly from mean-field predictions. In the Mott regime, we quantify the coherence associated to particle-hole excitations at finite tunnelling. In addition, we observe a perfectly contrasted atom bunching in the Mott state $g_2(0)$□2 from which we extract the two-particle volume of coherence. Finally, the strongly correlated nature of the quantum state in the critical region of the Mott transition manifests itself in distributions which we are difficult to interpret.

Expanding Bose-Einstein condensate in disorder: Role of many-body interactions for Anderson localization

Stefan Donsa[1], Ralf Wanzenböck[1], Peter Schlagheck[2], Harald Hofstätter[1], Othmar Koch[3], Joachim Burgdörfer[1], Iva Brezinova[1]

[1]*Institute for Theoretical Physics, Vienna University of Technology, Austria, EU*
[2]*CESAM Research Unit, University of Liege, Belgium, EU*
[3]*Faculty of Mathematics, University of Vienna, Austria, EU*

We numerically explore the expansion of a one-dimensional Bose-Einstein condensate (BEC) in speckle disorder [1,2]. In this setting we address two fundamental questions: First, are there unique signatures of Anderson localization in the presence of particle-particle interactions [3]? Second, which effect does the interplay between interactions and disorder have on the condensate state. Many-body localization in Fock space would suggest that the BEC is preserved. To tackle these questions, we employ on short time scales the truncated Wigner approximation [4] which gives access to many-body observables, and on longer times scales the Gross-Pitaevskii equation (GPE). We observe that the condensate state is almost completely depleted in the first few time steps during which interaction energy is converted into kinetic energy suggesting that many-body localization is not present in this system. On longer time scales, we compare different expansion scenarios in which particle-particle interactions are selectively switched on or off. Using typical experimental parameters, we show that the time scale for which the non-equilibrium dynamics of the interacting system begins to diverge from that of the non-interacting system exceeds the observation times up to now accessible in the experiment. We find evidence that the long-time evolution of the atomic cloud is characterized by (sub)diffusive spreading and a growing effective localization length of the cloud density suggesting that interactions destroy Anderson localization [3].

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Towards dispersive-probing enhanced measurement precision in quantum gas microscopes

Ottó Elíasson[1], Robert Heck[1], Jens Schultz Laustsen[1], Mario Napolitano[1], Romain Müller[1], Mark Bason[2], Carrie Weidner[1], Jan Arlt[1] and Jacob Sherson[1]

[1]Institute of Physics and Astronomy, Aarhus, Denmark
[2]Department of Physics and Astronomy, Sussex, United Kingdom

In the age of quantum simulation, experiments must give as tight bounds as possible to guide the construction of theoretical models describing complex many-body quantum systems. Experimentally, precision in all ultracold atom experiments is limited by both short- and long-term fluctuations in system parameters. Here, we present a number of ways in which dispersive imaging techniques can be used to reduce the effect of external parameter fluctuations. The techniques have so far been implemented on Bose-Einstein condensates (BECs) but work is currently underway to extend this to optical lattice dynamics in our operational quantum gas microscope.

First we demonstrate how dispersive measurements of ultracold atom clouds can be used to pin down the concrete atom number in a single experimental realization and thereby enhance the determination of the location of the phase transition to a BEC [1]. In another set of experiments custom microtrap arrays were created, and subsequently it was shown that individual traps could be probed dispersively. This allows for the creation of a quantum interaction region and a quantum sensor to detect environmental disturbances where some microtraps can then be used for high precision magnetometry. The dispersive scheme has allowed for single shot precisions of 2 nT in a total measurement time just below 1 ms. Utilizing the spatial resolution of the system gradients as low as 150 pT/µm can be detected [2].

The ultimate goal of this approach is to have an interaction region with complex optical lattice dynamics and one or more sensing regions surrounding it in which in-situ magnetometry is performed. As first steps in this direction we have demonstrated that our experiment both allows for single-site resolved detection of individual atoms and the dynamic control of a microtrap array in which we dynamically move the edges of a square array away from the remaining microtraps.

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Interaction induced fractionalization and topological superconductivity in the polar molecules anisotropic *t-J* model

S. Fazzini[1], L. Barbiero[2] and A. Montorsi[1]

[1]*Institute for condensed matter physics and complex systems, DISAT, Politecnico di Torino, I-10129 Turin, Italy*
[2]*Center for Nonlinear Phenomena and Complex Systems, Université Libre de Bruxelles, CP 231, Campus Plaine, B-1050 Brussels, Belgium*

We show that the interplay between antiferromagnetic interaction and hole motion gives rise to a topological superconducting phase. This is captured by the one dimensional anisotropic *t-J* model which can be experimentally achieved with ultracold polar molecules trapped onto an optical lattice. As a function of the anisotropy strength we find that different quantum phases appear, ranging from a gapless Luttinger liquid to spin gapped conducting and superconducting regimes. In presence of appropriate z-anisotropy, we also prove that a phase characterized by non-trivial topological order takes place. The latter is described uniquely by a finite non local string parameter and presents robust edge spin fractionalization. These results allow to explore quantum phases of matter where topological superconductivity is induced by the interaction.

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Quantum optics on the International Space Station

Kai Frye[1], **Dennis Becker[1]**, **Christian Schubert[1]**, **Thijs Wendrich[1]**, **Ernst Maria Rasel[1]**, **and BECCAL Team[1;2;3;4;5;6]**

[1]*Leibniz Universität Hannover, Hannover, Germany*
[2]*Universität Ulm, Ulm, Germany*
[3] *Ferdinand Braun Institut für Hochfrequenztechnik, Berlin, Germany*
[4]*Humboldt Universität zu Berlin, Berlin, Germany*
[5]*Johannes Gutenberg-Universität Mainz, Mainz, Germany*
[6]*ZARM, Universität Bremen, Bremen, Germany*

The multi-user and -purpose facility Bose-Einstein Condensate and Cold Atom Laboratory (BECCAL) will mark an important milestone for the ongoing quest of further advancing quantum optics into space. It will be launched to the International Space Station to perform a large variety of experiments with ultracold Rb and K atoms, therefore providing an extraordinary platform in a permanent microgravity environment.

The absence of gravitational sag and delta-kick collimated ensembles enable experiments unfeasible on ground and will lead to exciting observations beyond the scope of current lab experiments. German and US scientists jointly proposed research topics including atom interferometry, which will greatly benefit from extended free evolution times, atom optics, physics of quantum degenerate gases and their mixtures. The latter were so far studied only in Earth-bound experiments, where compensating gravity simultaneously for two different species is hardly achievable.

Here, the scientific capabilities and experimental layout is presented. We will discuss the design constraints set by an accommodation aboard the International Space Station and our approach to cover a broad range of possible experiments. This is realized by building upon the heritage of our drop tower experiments[1] and sounding rocket missions[2] as well as the experiences gathered through NASAs Cold Atom Laboratory[3].

The BECCAL project is a collaboration of LU Hannover, U Ulm, HU Berlin, FBH Berlin, JGU Mainz, DLR Institute of Space Systems Bremen and ZARM at U Bremen. It is supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under the grant numbers 50WP1431 and 50WP1700.

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Critical dynamics of photonic lattices in phase space

F. Gaggioli[1], M. Biondi[1] and G. Blatter[1]

[1] *Institute for Theoretical Physics, ETH Zürich*

The Bose-Hubbard model is a minimal description of various interacting many- body systems. Its nonequilibrium counterpart is an extension of the model to systems where particle loss and coherent driving play a fundamental role. Implementations of the driven dissipative Bose-Hubbard have been realised on photonic lattices, atomic setups and solid state systems. The interplay of interactions, hopping, drive and dissipation induces in this model a variety of nonequilibrium features, and is responsible for a novel example of dissipative phase transition. Our aim is to numerically simulate the steady state of this many-body system, in order to extract a phase diagram and investigate the role of intra-cavity hopping in the emergence of a cooperative phase transition which is absent in the case of a single cavity.

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Collisions between quantum droplets

G. Ferioli [1], G. Semeghini [1], A. Gallemí [2], L. Masi [1], G. Giusti [1], G. Modugno [1], M. Inguscio [1], A. Recati [2] and M. Fattori [1]

[1] *LENS, Firenze, Italy*
[2] *BEC Center, Trento, Italy*

We report on the study of collisions between self-bound droplets formed by an attractive mixture of ultracold ^{39}K atoms [1,2]. We distinguish two main outcomes of the collision, *i.e.* merging and separation, depending on the relative velocity of the colliding droplets. By characterizing the critical velocity which discriminates between the two cases as a function of the total atom number N, we recognize the presence of two distinct regimes. At small atom numbers the critical velocity increases for increasing N, showing that the droplets are in a compressible regime where the relevant energy scale is the droplet binding energy. For large atom numbers, instead, the critical velocity decreases with N, highlighting the crossover to a liquid-like incompressible regime, where the relevant energy scale is provided by the surface energy, and the behavior of colliding classical droplets is recovered [3]. We also provide a theoretical simulation of the experiment that confirms the results concerning the first experimental observation of the outcome in the collision between compressible droplets.

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Non-symmetric vortex equilibria in a Bose-Einstein condensate

Kwan Goddard Lee[1], Guillaume Gauthier[1], Matthew T. Reeves[2], Xiaoquan Yu[3], Ashton S. Bradley[2], Halina Rubinsztein-Dunlop[1], Matthew J. Davis[1], Tyler W. Neely[1]

[1] ARC Centre of Excellence for Engineered Quantum Systems (EQuS), School of Mathematics and Physics, University of Queensland, Brisbane 4072, Australia.

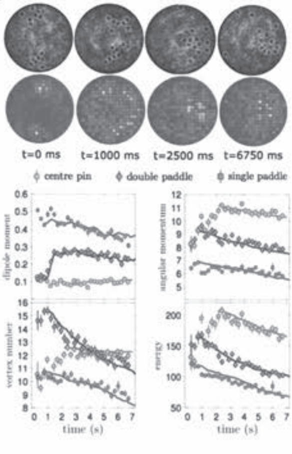
[2] Australian Research Council Centre of Excellence in Future Low-Energy Electronics Technologies, School of Mathematics and Physics, University of Queensland, St Lucia, QLD 4072, Australia.

[3] Department of Physics, Centre for Quantum Science, and Dodd-Walls Centre for Photonic and Quantum Technologies, University of Otago, Dunedin, New Zealand.

* kwan.goddardlee@gmail.com

In 1949 Lars Onsager explored a "toy model" of two-dimensional fluid flow by placing point-like vortices in a bounded container [1]; such a system has a bounded phase space which leads to clustering of same-signed vortices. The resulting vortex clusters are known as Onsager vortices which have negative thermodynamic temperatures. This gives qualitative insight into the stability of large vortices observed in many quasi two-dimensional fluid flows, such as the Great Red Spot of Jupiter. For certain vortex energies and angular momenta, the Onsager vortex equilibrium is positioned off-axis and does not share the symmetry of the trap [2]. The transition from a symmetric to a non-axisymmetric cluster resembles a second order phase transition [2].

The experimental apparatus at UQ facilitates highly controllable experiments on quasi two-dimensional Bose-Einstein Condensates (BECs). Quantised vortices in the BEC are very well described by point vortex models. We are able to create vortex clusters with control over their size and position. By modelling the vortices as point vortices we extract the energy and angular momentum, as well as clustering statistics during free evolution. We investigate the dynamics of same-sign vortex clusters initially positioned on and off axis. We also observe that an initially symmetric non-equilibrium vortex distribution dynamically equilibrates into a single non-axisymmetric cluster, in agreement with mean-field theory [2, 3], see Fig. 1. Our experimental results exhibit very good quantitive agreement with point vortex simulations, see Fig. 2.



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Selfgravitating BEC in external gravity: Modifying the selfinteraction constant

S. Gödtel[1], D. Giulini[1,2] and C. Lämmerzahl[1]

[1]ZARM, University of Bremen, Am Fallturm 1, D-28359 Bremen, Germany
[2] Leibniz University Hannover, Appelstraße 2, D-30167 Hannover, Germany

As an example of coupling gravity to a quantum mechanical system, we consider a selfgravitating Bose-Einstein-Condensate in an external gravitational field. Such systems are usually described by the Gross-Pitaevskii-Newton equation [1] which itself is a non-linear mean-field approximation.
We are now interested in corrections to the Gross-Pitaevskii equation, especially possible corrections to the coupling constant, due to both the external and the internal gravitational field. Such corrections have never been considered and we expect them to be non-linear as well as anisotropic. However, it is possible that they occur as a non-minimal coupling term.
Following rigorous mathematical derivations of the Gross-Pitaevskii equation [2], we start with the N-particle Schrödinger equation including an external gravitational field as well as a selfgravitating two-particle interaction. Using scattering theory, we determine the influence of both potentials onto the selfinteraction constant.
Furthermore, with the additional terms, we will be able to estimate a value for the particle density that gives a threshold for measurable gravitational effects in experiments with ultracold quantum gases.

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Meson gas theory of the *t-J* model

F. Grusdt[1,2], A. Bohrdt[1,2], Z. Zhu[2,3], T. Shi[4], M. Knap[1],
C. S. Chiu[2], G. Ji[2], M. Xu[2], M. Greiner[2], D. Greif[2],
J. Koepsell[5], G. Salomon[5], J. Vijayan[5], P. Sompet[5], I. Bloch[5,6], C. Gross[5],
and E. Demler[2]

[1] Department of Physics and Institute for Advanced Study, Technical University of Munich, 85748 Garching, Germany
[2] Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[3] Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[4] CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China
[5] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[6] Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 München, Germany

The complex interplay of spin and charge degrees of freedom is at the heart of high-temperature superconductivity and the complex many-body phases found in its vicinity in strongly correlated materials. Here we show on a microscopic level that this interplay gives rise to short-range hidden string order, which can be directly detected using quantum gas microscopy. We propose a new paradigm to describe the properties of individual holes moving in a spin-background with pronounced anti-ferromagnetic correlations, where the lattice geometry is dynamically modified along so-called geometric strings. Direct numerical and experimental evidence of such geometric strings will be presented. Our new insights suggest that strongly correlated quantum materials and high-energy particle physics are closely connected, and pave the way for developing a detailed microscopic understanding of the doped Fermi-Hubbard model in the future, both theoretically and experimentally.

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Quantum droplets in Bose-Bose mixture at finite temperature

N. Guebli[1] and A. Boudjemaa[1]

[1]*Department of Physics, Faculty of Exact Sciences and Informatics, Hassiba Benbouali University of Chlef P.O. Box 78, 02000, Ouled Fares, Chlef, Algeria.*

Self-bound quantum droplets are a newly discovered phase in the context of ultracold atoms. By following the original proposal by Petrov [Phys.Rev. Lett. 115, 155302 (2015)], and by the consideration of an attractive bosonic mixture, We study in this work the properties of droplet at finite temperature using the time-dependent Hartree-Fock-Bogoliubov theory which is a set of coupled nonlinear equations of motion for the condensate and its normal and anomalous fluctuations, we also discuss the effect of temperature at the droplet state..

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Spin Transport in a Mott Insulator of Ultracold Fermions

M. A. Nichols[1,2,3], L. W. Cheuk[2,4], M. Okan[1,2,3], T. Hartke[1,2,3], E. Mendez[1,2,3], T. Senthil[1], E. Khatami[5], H. Zhang[1,2,3], M. W. Zwierlein[1,2,3]

[1]*Department of Physics, MIT, Cambridge, Massachusetts 02139, USA*
[2]*MIT-Harvard Center for Ultracold Atoms, Cambridge, Massachusetts 02139, USA*
[3]*Research Laboratory of Electronics, MIT, Cambridge, Massachusetts 02139, USA*
[4]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[5]*Department of Physics and Astronomy, San José State University, San José, California 95192, USA*

Transport measurements provide a fundamental characterization of the dynamic response of a quantum system that is perturbed from equilibrium. In this poster, using a quantum gas microscope, we study spin transport in the 2D Fermi-Hubbard model, a model that is believed to capture essential features of high-temperature superconductivity. To realize the Fermi-Hubbard model, we confine ultracold 40K atoms in two hyperfine states with differing magnetic moments in a homogeneous square optical lattice. We then apply a magnetic field gradient and examine how the two spin distributions evolve in linear response in real time. For a half-filled system in the strongly correlated regime, we observe spin dynamics which are diffusive in nature and we extract both the spin conductivity and the diffusion coefficient. We compare these findings with novel numerical linked-cluster expansion (NLCE) calculations.[1]

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Singular loops and their non-Abelian geometric phases in spin-1 ultracold atoms

Bharath H. M, M. Boguslawski, M. Barrios, L. Xin and M. S. Chapman

Non-Abelian and non-adiabatic variants of Berry's phase have been pivotal in the recent advances in holonomic quantum gates, while Berry's phase itself is at the heart of the study of topological phases of matter. Here we use ultracold atoms to study the unique properties of spin-1 geometric phase [1]. The spin vector of a spin-1 system, unlike that of a spin-1/2 system, can lie anywhere on or inside the Bloch sphere representing the phase space. This suggests a generalization of Berry's phase to include closed paths that go inside the Bloch sphere. In [2], this generalized geometric phase was formulated as an SO(3) operator carried by the spin fluctuation tensor, developing on m=0 spin geometric phases [3] . Under this generalization, the special class of loops that pass through the center, which we refer to as singular loops are significant because their geometrical properties are qualitatively different from the nearby non-singular loops, making them akin to critical points of a quantum phase transition. Here we use coherent control of ultracold 87Rb atoms in an optical trap to experimentally explore the geometric phase of singular loops in a spin-1 quantum system [1].

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Transport in Optical Lattices with Flux

A. Hudomal[1], I. Vasić[1], H. Buljan[2], W. Hofstetter[3], and A. Balaž[1]

[1]Scientific Computing Laboratory, Center for the Study of Complex Systems,

Institute of Physics Belgrade, University of Belgrade, Serbia
[2] Department of Physics, Faculty of Science, University of Zagreb, Croatia
[3]Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany

Different condensed matter systems, such as electrons in a crystal lattice, can be simulated using ultracold atoms in optical lattices. Unlike electrons, atoms are electrically neutral and therefore do not feel the effects of magnetic field. Artificial gauge potentials have been recently realized in cold-atom experiments with periodically driven optical lattices [1,2]. In such systems, atoms subjected to a constant external force gain an anomalous velocity in the direction transverse to the direction of the applied force. Taking into consideration realistic experimental conditions, we perform numerical simulations in order to investigate the dynamics of atomic clouds and relate it to the Chern number of the effective model [3]. We consider incoherent bosons and the full time-dependent Hamiltonian. The effects of weak repulsive interactions between atoms are taken into account using the mean-field approximation. Our results show that driving, external force and interactions all cause heating and transitions to higher bands, which have significant effects on the dynamics. It turns out that weak interactions can be beneficial, because they make the momentum-space probability density more homogeneous.

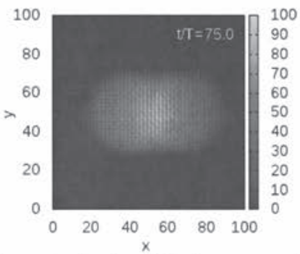

Fig. 1: Density profile of an atomic cloud during expansion dynamics after release from a trap in the presence of an artificial gauge field and external force.

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Dimensional crossover for the beyond-mean-field correction in Bose gases

Tobias Ilg[1], **Jan Kumlin**[1], **Luis Santos**[2], **Dmitry S. Petrov**[3], **and Hans Peter Büchler**[1]

[1]Institute for Theoretical Physics III and Center of Integrated Quantum Science and Technology, University of Stuttgart, Germany
[2] Institute for Theoretical Physics, Leibniz University Hannover, Germany
[3] LPTMS, CNRS, Université Paris Sud, Université Paris-Saclay, France

We present a detailed beyond-mean-field analysis of a weakly interacting Bose gas in the crossover from three to low dimensions. We find an analytical solution for the energy and provide a clear qualitative picture of the crossover in the case of a box potential with periodic boundary conditions. We show that the leading contribution of the confinement-induced resonance is of beyond-mean-field order and calculate the leading corrections in the three- and low-dimensional limits. We also characterize the crossover for harmonic potentials in a model system with particularly chosen short and long-range interactions and show the limitations of the local-density approximation. Our analysis is applicable to Bose-Bose mixtures and gives a starting point for developing the beyond-mean-field theory in inhomogeneous systems with long-range interactions such as dipolar particles or Rydberg- dressed atoms.

Transverse magnetization effect of the spin-imbalanced Hofstadter-Hubbard model

B. Irsigler, J.-H. Zheng, M. Hafez-Torbati, and W. Hofstetter

Institut für theoretische Physik, Goethe-Universität, Frankfurt am Main, Germany

We investigate the population spin-imbalanced fermionic Hofstadter-Hubbard model in the strongly interacting regime such that charge degrees of freedom are frozen. We find an exotic spin structure of the unit cell while varying the population imbalance. Remarkably, this spin structure exhibits a transverse magnetization perpendicular to the magnetization induced by the population imbalance. For a plaquette flux of 1/4 we find a stable 4-sublattice structure and for 1/3 we observe a phase transition from an anti-ferromagnetic phase to a diagonal 3-periodic spin density wave, where in the latter the transverse magnetization response vanishes.

Non-equilibrium dynamics of interacting Bosons in an optical lattice

C. Baals[1,2], J. Benary[1], J. Jiang[1] and Herwig Ott[1]

[1]Department of Physics and Research Center OPTIMAS, TU Kaiserslautern, 67663 Kaiserslautern, Germany

[2] Graduate School Materials Science in Mainz, 55128 Mainz, Germany

We study the non-equilibrium dynamics of ultracold Bose gases in optical lattices using a scanning electron microscope. In the last experiment we characterized the emerging steady-states of a driven dissipative Josephson junction array, realized with a BEC in a one-dimensional optical lattice. By locally applying dissipation using the electron beam at an initially full site, we can induce a superfluid response which keeps the respective site filled. This can be seen as an extension of the paradigm of Coherent Perfect Absorption (CPA). CPA refers to the complete extinction of incoming radiation by spatially localized absorber embedded in a wave-guiding medium. Our current work is focused on the generation and stabilization of dark solitons in 3D. To imprint the phase step of π onto a BEC we use a Digital Micromirror Device to create a sharp edge in the beam profile of a 532nm laser. We will then make use of the electron beam as a source of local dissipation to stabilise the dark soliton.

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Towards a continuously operating matter wave interferometer for inertial sensing

H. Keßler[1], **M. Moreno**[1], **C. Beli**[1], **R. Shiozaki**[2] **and P. W. Courteille**[1]

[1]*Instituto de Física USP, São Carlos, Brazil*
[2] *Departamento de Física UFSCAR, São Carlos, Brazil*

Cold atoms inside an optical cavity, operating in the regime of strong cooperative coupling respond to an external force by opto-mechanical Bloch oscillation, which can be directly observed in the light leaking out of the cavity [1]. Previous theoretical work predicts that the frequency of this oscillation matches with that of conventional Bloch oscillations [2]. This *in situ* monitoring helps to increase the data acquisition speed in precision force measurements. In São Carlos we are setting up an experiment with Strontium atoms inside a ring-cavity. Due to the magnetic moment of the ground state equal to zero and the very small s-wave scattering length, Strontium is an ideal element for an application in a gravimeter. In contrast to a linear cavity, in a ring-cavity it is possible to probe the momentum state of the atoms with a running wave and the optical lattice potential is separated from the probe light.

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Thermodynamics and structural transition of binary atomic Bose-Fermi mixtures: A path-integral study

Tom Kim[1] and Chih-Chun Chien[1]

[1] *School of Natural Sciences, University of California, Merced, California 95343, USA*

Experimental realizations of a variety of atomic binary Bose-Fermi mixtures have brought opportunities for studying composite quantum systems with different spin statistics. The binary atomic mixtures can exhibit a structural transition from a mixture into phase separation as the boson-fermion interaction increases. We apply a large-N expansion theory to binary Bose-Fermi mixtures. The large-N theory is written in a path-integral. For single component bosons, the theoretical results compared favorably with available experimental data[1]. For binary boson-fermion mixtures, thermodynamic quantities can be derived in a broad range of temperature and interaction beyond mean field approximation. The structural transition occurs when a loop emerges in the effective potential, and the volume fraction of phase separation can be determined by the lever rule. As concrete examples, we present the phase diagrams of ^{6}Li − ^{7}Li and ^{6}Li − ^{41}K mixtures. We perform the calculations in a box potential and harmonic trap at zero and finite temperatures. Due to the compressible densities of atomic gases, the construction of phase separation requires a balance of mechanical and diffusive equilibrium, which are automatically satisfied in conventional liquid or solid mixtures. We use the local density approximation to map out the finite-temperature density profiles for harmonically trapped mixtures and present typical profiles, including the mixture, partially separated phases, and fully separated phases[2].

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Elucidating scattering resonances with an ultracold atom collider

R. Thomas, M. Horvath, A. B. Deb and N. Kjærgaard

Department of Physics, University of Otago, New Zealand (nk@otago.ac.nz)

Since its introduction by Geiger, Marsden, and Rutherford the scattering experiment has become one of the most widely used techniques in modern physics. A particularly interesting phenomenon of quantum scattering are resonances, which arise from coupling between free and bound states of a physical system. We present results from experiments that investigated two different types of scattering resonances that occur in the collision of ultracold atoms: shape resonances [1,2] and Feshbach resonances [3,4]. Because of the pristine nature of the ultracold systems, our experiments distill these resonance phenomena into their quintessential form (Figure 1 shows the example of the swing from extinction to enhancement in scattering about a Fano-Feshbach resonance resulting from quantum interference between outgoing amplitudes).

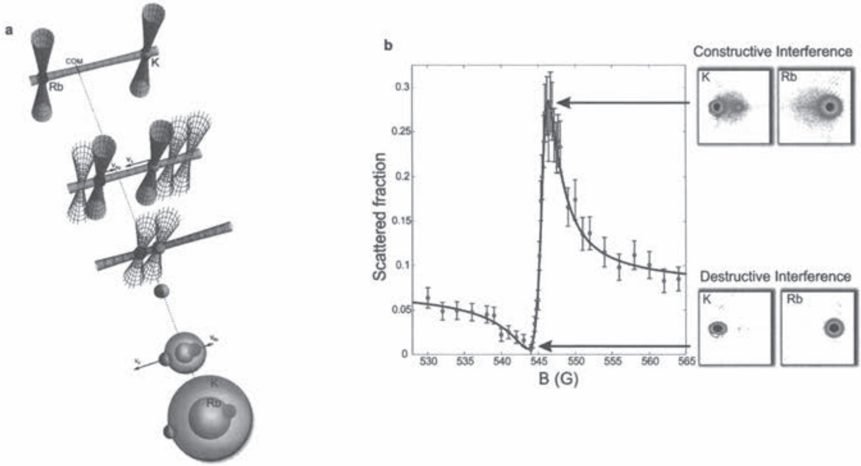

Figure 1 | K+Rb scattering in an atom collider based on steerable optical tweezers. **a** Schematic of collider protocol [4]. **b** Scattered fraction of atoms as a function of magnetic field around a Feshbach resonance for atoms colliding at an energy of $E/k_B \sim 50\ \mu K$ displaying the archetypical Fano lineshape.

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Towards the Bose Polaron in an ultracold Bose-Fermi mixture of ^{133}Cs and ^{6}Li

<u>L. Klaus</u>, B. Tran, E. Lippi, M. Gerken, B. Zhu and M. Weidemüller

Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany

Landau and Pekar proposed in 1946 that electron moving through a lattice will interact with the phonons and will give rise to a quasiparticle called polaron - an electron dressed by a cloud of phonons [1]. These polarons can have a significantly different effective mass and therefore lead to modified electronic and thermal transport inside the material. These systems can be simulated in ultracold atom experiments and can be tuned widely from weakly to strongly and attractive or repulsive interactions.

In our experiment we study the Bose polaron in an ultracold Bose-Fermi mixture of ^{133}Cs and ^{6}Li atoms with a large mass difference. The Bose polaron is a quasiparticle that describes a single Li impurity which is immersed into a Cs BEC and interacts with its phonon excitations. Via Li-Cs Feshbach resonances we can tune the interparticle interaction strength and change the sign of interaction, thus enabling us to investigate both attractive and repulsive polarons. Recent theoretical investigations [2, 3] have suggested that, for a Li-Cs mixture, signatures of Efimov physics are expected in the properties of the Bose polaron.

We describe the creation of the Cs BEC by means of evaporative cooling in an optical dipole trap and a magnetic gradient. In order to reach a high phase-space density we modify our trapping potential by reducing the magnetic gradient. We also describe our scheme to immerse our Li cloud into the Cs BEC, to guarantee a high overlap of both clouds. Furthermore, we give an overview of our approach towards the measurements of the Bose polaron's properties such as its spectral function and its quasiparticle residue, aiming to show the emergence of Efimov physics in a many-body system for the first time.

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Direct imaging of magnetic Hubbard polarons

J. Koepsell[1], P. Sompet[1], J. Vijayan[1], G. Salomon[1], F. Grusdt[2], E. Demler[2], I. Bloch[1,3] and C. Gross[1]

[1] *Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[2] *Harvard university, Cambridge, MA, USA*
[3] *Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 München, Germany*

Polarons are among the most successful and renowned theoretical concepts to treat an overwhelming diversity of complex many-body-phenomena. Yet, a direct observation via real space correlations of such quasiparticles is lacking. Here we report the direct microscopic observation of a magnetic polaron in the doped Fermi-Hubbard model, harnessing the full single-site spin and density resolution of our ultracold-atom quantum simulator. We reveal the dressing of mobile impurities by a local reduction in antiferromagnetic order, which is caused by the competition between kinetic and magnetic energy. Using an optical tweezer to pin the position of a single dopant, we demonstrate that indeed dopant delocalization is responsible for the modification of magnetic correlations. Furthermore, we perform a comparison of the local spin environment to exact diagonalization and an effective string model at finite temperature, which predict the same polaron size as observed in the experiment on the order of one lattice site. With this work we pave the way towards microscopic studies of polaron-polaron interactions and their relation to the pseudogap and strange metal phase.

Singular Floquet scattering with atomic interactions

H. Landa[1]

[1] *Institut de Physique Théorique, Université Paris-Saclay, CEA, CNRS, 91191 Gif-sur-Yvette, France*

We study quasi-bound states and scattering with short-range potentials in three dimensions, subject to an axial periodic driving. We find that poles of the scattering *S* matrix can cross the real energy axis as a function of the drive amplitude, making the *S* matrix nonanalytic at singular points, similar to "spectral singularities" (or "exceptional points"). For the corresponding quasi-bound states that can tunnel out of (or get captured within) a potential well, this results in a discontinuous jump in both the angular momentum and energy of emitted (absorbed) waves. We also analyze elastic and inelastic scattering of slow particles in the time dependent potential. For a drive amplitude at the singular point, there is a total absorption of incoming low energy (*s* wave) particles and their conversion to high energy outgoing (mostly *p*) waves. These results apply broadly to particles interacting via power law forces and subject to periodic fields, e.g. co-trapped ions and atoms.

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Towards Direct Laser Cooling of Barium Monofluoride

R. Albrecht, T. Sixt, L. Hofer, M. Scharwaechter and T. Langen

5. Physikalisches Institut and IQST, University of Stuttgart, Stuttgart, Germany

We present a new experimental setup for the laser cooling and trapping of barium monofluoride molecules. Laser cooling of molecules had long been considered impossible due to their complex vibrational and rotational level structure. However, beneficial Franck-Condon factors and selection rules allow for optical cycling in many molecular species [1-5], including barium monofluoride [6]. The molecules are generated through laser ablation in a 4K cryostat and precooled by collisions with a helium buffer gas. This results in a cold and intense beam that provides ideal starting conditions for transversal laser cooling, slowing and subsequent loading of a 3D magneto-optical trap. The resulting cold gas of heavy diatomic molecules will pave the way for a large number of novel and interdisciplinary applications ranging from few- and many-body physics to cold chemistry and tests of fundamental symmetries.

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Bose-Einstein condensates in Toroidal Guiding Potentials for ATOMTRONICS Devices

Daniel Laukhardt[1], Felix Schmaltz[2], Felix Weigand, Dominik Pfeiffer, and Gerhard Birkl

[1, 2]Institut für Angewandte Physik, Technische Universität Darmstadt, Schlossgartenstraße 7, 64289 Darmstadt

We present a novel type of toroidal guiding potential for BEC-based coherent matter waves applicable for atom interferometry or ATOMTRONICS devices such as atomic SQUIDS.

Exploiting the effect of conical refraction in biaxial crystals, we are able to create various types of light field patterns, which can act as dipole force mediated toroidal matter waveguides. Depending on laser beam and crystal parameters, the topology and dimension of these waveguides can be controlled.

Changing the waist of the impinging laser beam, the conical refraction light field, using blue-detuned light, can be transformed from a harmonical to a toroidal trapping potential. With a flexible digital micromirror device (DMD) system, we can realize the adiabatic transfer of a BEC from a simply connected to a multiply connected trapping topology.

By using red-detuned light the topology of the now attractive conical refraction light field can be formed with spatial apertures that freely programmable onto the DMD. The possibility to address every single micromirror at a frequency of up to 4000 Hz enables a maltitude of manipulating options for the light field, such as rotating or splitting sequences for BECs.

Such a rotating matter wave can be used to probe superfluidity, vortex-like behaviour, and matter-wave interference of confined BECs in a dynamically adjustable fashion.

Emerging quantum-many body effects in a hybrid atom-optomechanical system

N. Mann[1], M. Reza Bakhtiari[1], A. Pelster[2], and M. Thorwart[1]

[1] *I. Institut für Theoretische Physik, Universität Hamburg, Jungiusstraße 9, 20355 Hamburg, Germany*

[2] *Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Erwin-Schrödinger Straße 46, 67663 Kaiserslautern, Germany*

When a vibrational mechanical mode of a semitransparent nanomembrane interacts optomechanically with light in a cavity, and when in the optical lattice of the out-coupled light, an ultracold Bose gas is placed, a hybrid quantum many-body system is formed [1]. The collective dynamics of the atomic ensemble is effectively coupled to the displacement of a nanomechanical oscillator, which follows formally after adiabatically eliminating the light field in a Hamiltonian operator. Two different configurations are possible: In the external state coupling scheme, the motional degrees of freedom of the atoms are addressed. The hybrid system shows an interesting competition between the force localizing the atomic motion and the membrane displacement. At a critical atom-membrane coupling, a nonequilibrium quantum phase transition from a localized symmetric state of the atom cloud to a shifted symmetry-broken state occurs [1].

Alternatively, in the internal state coupling scheme, internal atomic degrees of freedom are addressed. This offers the advantage that the energy gap between two internal states can be tuned to resonance with the low-frequency vibrational motion of the nanooscillator. Such a close-to-resonant coupling gives rise to strong displacement squeezing of the membrane [2]. This is shown within a path-integral formalism, which also reveals that squeezing is enhanced by finite atom-atom interactions. Thereby, we treat the interaction by a Bogoliubov theory to map the condensate modes to a harmonic bath with an interaction-dependent spectral density. In addition, we find a nonequilibrium quantum phase transition between phases of different collective behavior [3]. Interestingly, the order of the phase transition can be easily changed by tuning the transition frequency between the internal states. Below a certain critical coupling, all the atoms occupy the energetically lower internal state. At the critical point, a nonequilibrium quantum phase transition happens. The discontinuous phase transition regime is divided into region with a preferred and a bistable polarization of the atoms. Moreover, hysteresis is obtained by adiabatically tuning the coupling strength in the regime of a first order phase transition.

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Dimensional phase transition from 1D quantum liquids to 3D condensates

P. Matveeva [1], **I. Schneider** [1], **S. Eggert** [1], **A. Pelster** [1], **D. Morath** [1], **and D. Straßel** [1,2]

[1] *Technical University Of Kaiserslautern, Kaiserslautern, Germany*
[2] *Competence Center for High Performance Computing, Fraunhofer ITWM, Kaiserslautern, Germany*

We consider weakly coupled strongly interacting quantum chains, such as quantum wires, anisotropic ultracold gases, or quasi-1D spin-chain compounds. It is known that a phase transition from the 1D Luttinger liquid behavior to a 3D ordered states can be qualitatively descibed by a chain mean field theory to determine the critical temperature, but the quantitative corrections and the range of validity is not well established. We therefore simulate the transition using a fully 3D microscopic model with very large scale quantum Monte Carlo calculations and compare with theoretical prediction including higher order terms in the chain mean field theory. We not only determine the very strong quantitative corrections, but also find a new regime of low density behavior where long range quantum correlations between the chains dominate the behavior, which leads qualitatively different powerlaws as a function of interchain couplings.

Superfluidity in density imbalanced bilayers of dipolar fermions

Azadeh Mazloom[1] and **Saeed H. Abedinpour [2]**

[1] *Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[2] *Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan, Iran*

We study the zero temperature phase diagram of an imbalanced bilayer of dipolar fermions [1]. We consider perpendicularly aligned identical dipoles in two layers and investigate the effect of population imbalance on the ground state phase at different layer spacings and average densities. The attractive part of the interlayer interaction could lead to the BEC-BCS crossover and the Fermi surface mismatch between two layers results in interesting uniform and non-uniform superfluid phases, which we have investigated here using the BCS mean-field theory together with the superfluid-mass density criterion. The density imbalance reduces the pairing gap. At low densities, where the system is on the BEC side of the crossover, this reduction is quite smooth while a dense system rapidly becomes normal at intermediate density polarizations. Stable homogeneous superfluidity is predicted to appear on the phase diagram when the dipolar length exceeds both the layer spacing and the average intralayer distance between dipoles, a regime which should be readily accessible experimentally. This homogeneous superfluid phase becomes unstable at intermediate densities and layer spacings. We have also examined that these uniform and inhomogeneous superfluid phases survive when the effects of intralayer screenings are also incorporated in the formalism.

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Derivation and Application of Stochastic Ehrenfest Relations from the Stochastic Projected Gross-Pitaevskii Equation

R. G. McDonald and **A. S. Bradley**

The Dodd-Walls Centre for Photonic and Quantum Technologies, Department of Physics, University of Otago, Dunedin, New Zealand

The stochastic projected Gross-Pitaevskii equation (SPGPE) is a classical field theory for finite-temperature Bose gases where interaction with the thermal cloud is characterized by two distinct processes, known as number-damping and energy-damping [1]. While number-damping effects (also known as simple growth) have been explored extensively (e.g. [2-4]), the energy-damping contribution is beginning to attract significant interest (e.g [5-7]). We use Ito change of variables to obtain stochastic Ehrenfest relations from the SPGPE. These relations include contributions from both number-damping and energy-damping reservoir interactions. These stochastic Ehrenfest relations suggest that the contribution from energy-damping may be significant and distinguishable from the number-damping contribution in some systems. We apply the stochastic Ehrenfest relations to a harmonically trapped degenerate finite-temperature Bose gas, finding analytic solutions for the position and momentum correlations. These are compared favourably to numerical results found by simulation of the SPGPE.

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The space atom laser: An isotropic source for ultra-cold atoms in microgravity

Matthias Meister[1], **Albert Roura**[1], **Ernst M. Rasel**[2] **and Wolfgang P. Schleich**[1]

[1]*Insitute of Quantum Physics, Ulm University, Ulm, Germany*

[2] *Institute of Quantum Optics, Leibniz University Hannover, Hannover, Germany*

Up to now atom-laser experiments have been performed in earth-bound laboratories, where the dominant force acting on the outcoupled atoms is gravity, which results in a directed and accelerated beam of atoms leaving the condensate. Here we propose to enter a completely new regime for the atom laser by taking advantage of NASA's Cold Atom Laboratory (CAL): thanks to the microgravity conditions on the ISS it is possible to create a unique shell-like atom laser which slowly expands away from the initial Bose-Einstein condensate (BEC) driven only by the repulsive interaction between the atoms.

Based on radio-frequency outcoupling we have developed a scheme that enables the generation of a slowly expanding shell of atoms featuring an isotropic distribution both in position and momentum even for an initially anisotropic BEC. This output is achieved by resonantly outcoupling at the very edge of the BEC with relatively small coupling strength to establish a spatially well-localized and state-selective outcoupling process.

We have numerically studied atom-laser experiments in microgravity taking into account higher-order contributions to the Zeeman effect and fluctuations of the number of particles and the Rabi frequency as well as varying magnetic fields. In this way we have identified a promising parameter regime for a successful realization of the space atom laser during the CAL flight campaign starting in fall 2018.

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Cold-atom-based implementation of the Dicke model in the ultra-strong coupling regime

Y. Meng,[1] A. Dareau,[1] P. Schneeweiss[1] and A. Rauschenbeutel[1,2]

[1]TU Wien - Atominstitut, Vienna, Austria
[2] Department of Physics, Humboldt-Universität zu Berlin, Berlin, Germany

The interaction between quantum emitters and a single quantized electromagnetic field mode is at the heart of quantum optics. When the interaction strength approaches the frequency of the mode, the so called ultra-strong coupling regime emerges, where new physical phenomena are expected. To investigate light-matter interaction at this extremely large coupling strength, tunable system parameters and preparation of the initial state are highly desirable. For this purpose, we demonstrate that cold atoms constitute a promising model system where mechanical excitations are used as an analogue of the photons. Atoms confined in optical micro trapping potentials can experience strong gradients of the vector ac Stark shift which act as spatially varying fictitious magnetic fields. The fictitious field gradients result in a coupling between the atoms' motion and spin, which is formally equivalent to the atom-photon coupling encountered in cavity QED [1].

We will discuss experiments taking advantage of this spin-motion coupling to manipulate cold Cesium atoms in a nanofiber-based optical trap. First, we have implemented degenerate Raman cooling, which we can either do via an external or a fiber-guided light field [2]. The final temperature of the atoms can be inferred from a fluorescence spectroscopy measurement. It indicates cooling of the atoms close to the motional ground state in all spatial dimensions. Second, we record fluorescence spectra for different values of the offset magnetic field, which corresponds to changing the atom-resonator detuning in a conventional cavity QED setting [3]. In the experiment, we obtain coupling strengths which are a significant fraction of the mode (trap) frequency, which sets our system clearly in the ultra-strong coupling regime. Furthermore, we have demonstrated the coupling strength can be readily and independently tuned in situ. Beyond fundamental interest, our results pave the way for implementing protocols and applications that exploit extreme coupling strengths.

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Many-Body Polaron Dynamics

S. I. Mistakidis[1] , A.G.Volosniev[2] , N.T. Zinner[3,4], Th. Busch[5] , G.C. Katsimiga[1], G.M. Koutentakis[1,6], and P. Schmelcher[1,6]

[1]Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[2] Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany
[3] Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
[4] Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark
[5] Quantum Systems Unit, Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa 904-0495, Japan
[6] The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

We unravel the existence and correlation properties of one dimensional harmonically trapped repulsive Fermi and Bose polarons. In the case of fermions a characterization of these quasiparticle-like states is achieved by simulating the impurity's radiofrequency spectrum and subsequently extracting their lifetime and residua. The occurrence of both single and multiple polarons that are entangled with their environment is observed while a special emphasis is placed regarding their induced interactions. Turning to bosons we investigate the quench dynamics of impurity atoms in a one-dimensional trapped Bose gas. We show that inhomogeneity can be taken into account by an effective one-body model where both the mass and the string constant are renormalized. We propose an effective single particle Hamiltonian and use many-body simulations to explore its validity. Moreover, we inspect the dynamical dressing of a single impurity by monitoring its nonequilibrium dynamics, being a superposition of a spin-up and a spin-down state, when coupled to the bosonic environment. We expose the presence of entanglement in the system, and offer a way to probe such a many-body feature by connecting its manifestation to the spin polarization.

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Weakly Interacting Bose Gas on a Sphere

N. Móller[1], V. Bagnato[2], and A. Pelster[1]

[1]Research Center OPTIMAS and Department of Physics, Technische Universität Kaiserslautern, Germany
[2]Institute of Physics of São Paulo, University of São Paulo, São Carlos, Brazil
E-mail: natalia.smoller@gmail.com

Here we explore how to describe theoretically a weakly interacting Bose gas on a sphere. In order to derive the corresponding many-body field theory we start with considering a radial harmonic trap, which confines the three-dimensional Bose gas in the vicinity of the surface of a sphere. Following the notion of dimensional reduction as outlined in Ref. [1] we assume a large enough trap frequency so that the radial degree of freedom of the field operator is fixed despite of thermal and quantum fluctuations to the ground state of the radial harmonic trap and can be integrated out. With this we obtain an effective many-body field theory for a Bose-Einstein condensate on a quasi two-dimensional sphere, where the thickness of the cloud is determined self-consistently.

As a first example we determine the critical temperature of a Bose Gas on a sphere and discuss its dependence on both the particle number and the radius of the sphere. In the limit of an infinitely large radius we recover the case of a quasi two-dimensional plane with a vanishing critical temperature in accordance with the Mermin-Wagner theorem [2]. Afterwards, we analyze at zero temperature the mean-field physics of a Bose-Einstein condensate on a sphere by deriving the underlying time-dependent Gross-Pitaevskii equation. Performing a linear stability analysis yields the corresponding collective excitations. The obtained theoretical results are relevant for designing an experimental realization with a mixture of two Bose gases, where the first one is in the state of a Bose-Einstein condensate forming a rigid sphere, while the other Bose gas lies on top of it as a thin film. Such an experiment would demonstrate that many-body physics on curved manifolds could be simulated with ultracold quantum gases.

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Ground state phases and excitation of Rashba spin-orbit coupled Bose-Einstein condensates with Rabi mixing in two-dimensions

R. Ravisankar and P. Muruganandam

Department of Physics, Bharathidasan University, Tiruchirappalli 620 024, India

In the talk, we present the ground state phase diagram and excitation spectrum of Rashba spin-orbit coupled Bose-Einstein condensates with Rabi coupling in quasi-two dimension. We analyze the role of the parameters, namely, spin-orbit and Rabi couplings with fixed inter- and intra-species interactions in a weak harmonic trap by numerically solving the coupled two-dimensional Gross-Pitaevskii equations. Particularly, different phases such as plane wave, zero momentum phase, an intermediate state, half-quantum vortex, semi-vortex and stripe wave states were found by fixing a weak intra- and strong inter-species interactions. The number of phases found to reduce when the intra- and interspecies interaction strengths are of the same order. Further, we report the collective excitation spectrum of the system gives phonon-roton-maxon like excitations in the k_x-momentum direction, and stable-unstable regions in k_y-momentum direction by interplaying with the parameters.

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Temperature dependent density profiles and collective oscillations of dipolar droplets

E. Aybar and M.Ö. Oktel

Department of Physics, Bilkent University, Ankara, Turkey

Recently, trapped dipolar gases were observed to form high density droplets in a regime where mean field theory predicts collapse. These droplets present a novel form of equilibrium where quantum fluctuations are critical for stability. So far, the effect of quantum fluctuations have only been considered at zero temperature through the local chemical potential arising from the Lee--Huang--Yang correction. We extend the theory of dipolar droplets to non-zero temperatures using Hartree--Fock--Bogoliubov theory, and show that the local compressibility is strongly affected by temperature fluctuations. Hartree--Fock--Bogoliubov theory, together with local density approximation for excitations, reproduces the zero temperature results. The system can still be described with a modified GP equation at low temperatures if that the total depletion remains small. We find that both the transition between the droplet and trapped states, and the collective oscillation frequencies of the droplet can change dramatically even at typical experimental temperatures (T ~ 100 nK).

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Cavity-induced emergent topological spin textures in a Bose-Einstein condensate

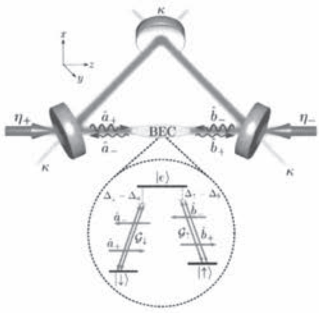
S. Ostermann[1], H.-W. Lau[2,3], H. Ritsch[1], F. Mivehvar[1]

[1]Institut für Theoretische Physik, Universität Innsbruck, Technikerstraße 21 a, 6020 Innsbruck, Austria

[2] Max-Planck Institute for the Physics of Complex Systems, Nöthnizer Straße 38, 01187 Dresden, Germany

[3] Institute for Quantum Science and Technology and Department of Physics and Astronomy, University of Calgary, Calgary T2N 1N4, Alberta, Canada

The coupled nonlinear dynamics of ultracold quantum matter and electromagnetic field modes in an optical resonator exhibits a wealth of intriguing collective phenomena. Here we study a Λ-type, three-component Bose-Einstein condensate coupled to four dynamical running-wave modes of a ring cavity, where only two of the modes are externally pumped. However, the unpumped modes play a crucial role in the dynamics of the system due to coherent back-scattering of photons. On a mean-field level we identify three fundamentally di_erent steady-state phases with distinct characteristics in the density and spatial spin textures: a combined density and spin wave, a continuous spin spiral with a homogeneous density, and a spin spiral with a modulated density. The spin-spiral states, which are topological, are intimately related to cavity-induced spin-orbit coupling emerging beyond a critical pump power. The topologically trivial density-wave{spin-wave state has the characteristics of a supersolid with two broken continuous symmetries. The transitions between different phases are either simultaneously topological and first order, or second order. The proposed setup allows the simulation of intriguing many-body quantum phenomena by solely tuning the pump amplitudes and frequencies, with the cavity output fields serving as a built-in nondestructive observation tool.



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Dynamical Equilibration and Critical Exponents in Quenched Quantum Gases

N.P. Proukakis[1]

[1]*Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne, UK*

The formation of an equilibrium state from an uncorrelated thermal one through the dynamical crossing of a phase transition is a central question of quantum many-body physics. During such crossing, the system breaks its symmetry by establishing numerous uncorrelated regions separated by spontaneously generated defects, whose emergence obeys a universal scaling law with quench duration. The evolution and interactions of such defects, affected by the system geometry and dimensionality are crucial to the way in which the quenched system reaches its final state.

Considering, firstly, the quenched crossing of the Bose–Einstein condensation phase transition in an elongated ultracold atomic gas, in the context of the Trento experiments, we provide a full numerical characterisation and visualization of the entire non-equilibrium process, addressing subtle issues and demonstrating the quench-induced decoupling of condensate atom number and coherence growth during the re-equilibration process [1].

In the context of instantaneously-quenched homogeneous two-dimensional driven-dissipative exciton-polaritons, we demonstrate that, despite the system's driven-dissipative nature, it exhibits the Berezinskii-Kosterlitz-Thouless phase transition and fulfills the dynamical scaling hypothesis, with the dynamical critical exponent $z=2$ with explicit logarithmic corrections playing a key role [2], consistent with the 2D XY model.

This work was funded by EPSRC and performed with I-K Liu, S-C Gou (National Changhua University of Education, Taiwan), S Donadello, G Lamporesi, G Ferrari, S-C Gou, F Dalfovo and I Carusotto (BEC Centre, Trento, Italy), P Comaron (Newcastle University), G Dagvadorj, A Zamora and M H Szymanska (University College London).

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Observation of universal dynamics in a spinor gas far from equilibrium

Maximilian Prüfer[1], Philipp Kunkel[1], Helmut Strobel[1], Stefan Lannig[1], Daniel Linnemann[1], Christian-Marcel Schmied[1], Jürgen Berges[2], Thomas Gasenzer[1], and Markus K. Oberthaler[1]

[1] *Kirchhoff-Institut für Physik, Universität Heidelberg*
[2] *Institut für Theoretische Physik, Universität Heidelberg*

Far from equilibrium different scenarios on the way to equilibrium have been identified. Here, we present a new scenario featuring universal dynamics associated to the existence of non-thermal fixed points. We access and study this regime experimentally for a Bose-Einstein condensate of ^{87}Rb in the $F = 1$ hyperfine manifold with ferromagnetic interactions. We quench an experimental control parameter, which leads to a build-up of excitations in the transversal spin. We identify a regime in the time evolution where the in-plane orientation of this spin becomes the relevant dynamical degree of freedom. Spatially resolved read-out allows the momentum resolved study of correlation functions which show rescaling in time and space – the dynamics is solely captured by a universal scaling function and associated exponents. We experimentally identify an emergent conserved quantity which is transported towards low momentum scales. By preparing different initial conditions we confirm that the non-thermal scaling involves no fine tuning of parameters.

Out-of-equilibrium dynamics of ultracold bosons in time-dependent random potentials

M. Radonjić[1,2] and A. Pelster[1]

[1]*Department of Physics, Technische Universität Kaiserslautern, Germany*
[2]*Institute of Physics Belgrade, University of Belgrade, Serbia*

We investigate perturbatively the impact of time-dependent random potentials on a weakly interacting Bose gas at zero temperature. Generically, a random potential yields, on the ensemble average, a depletion of the condensate. It stems from the localization of bosons in the respective minima of the disordered landscape and is usually quantified by a Bose-glass order parameter [1] in close analogy to the well-known Edwards-Anderson order parameter for spin-glasses [2]. A time dependence of the random potential leads in addition to an out-of-equilibrium dynamics of the condensate depletion.

Here we study a smooth quench of a spatially delta-correlated disordered potential from an initial disorder-free state of a uniform Bose gas. Depending on the quench rise time we focus on two limiting cases: adiabatic and sudden quench. In the long-time limit the former scenario reproduces the static disorder equilibrium case [3], while the latter leads to the formation of a non-equilibrium steady state, which turns out to have an even larger condensate depletion.

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Non-autonomous Bright Matter-Wave Solitons in Spin-2 Bose-Einstein Condensates

R. Babu Mareeswaran and T. Kanna

PG and Research Department of Physics, Bishop Heber College, Tiruchirappalli – 620023, Tamil Nadu, India

We consider spinor Bose-Einstein condensates (BECs) with hyperfine spin F = 2 described by a general five-component Gross-Pitaevskii (5-GP) equation and construct an exact bright matter-wave soliton solution by using a non-standard type of Hirota's bilinearization method with an auxiliary function. The obtained solitons are classified into ferromagnetic and polar solitons which support various density profiles ranging from a single-hump to double-humps and flat-top structures. Next, we consider a non-autonomous spin-2 BEC system governed by 5-GP equations with time-dependent nonlinearity (mean-field and spin-exchange interactions) coefficients which can be experimentally tuned by Feshbach resonance mechanism and transform it into an autonomous integrable 5-GP equation with constant coefficients by using the similarity transformations. From the obtained soliton solutions, their dynamics in non-autonomous spinor condensates is investigated. To elucidate the understanding, we choose a periodically modulated nonlinearity and explore their importance in the dynamics of matter-wave solitons.

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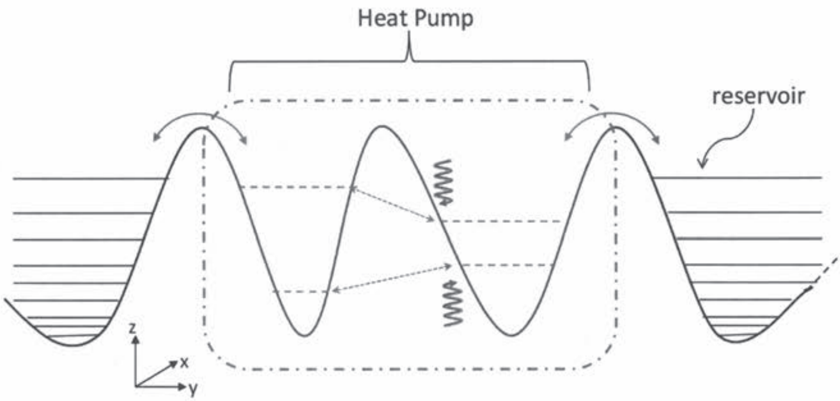
Design and characterization of a quantum gas heat pump

Arko Roy, Daniel Vorberg, and André Eckardt

Max Planck Institute for the Physics of Complex Systems, Dresden, Germany
E-mail: arko@pks.mpg.de

We propose a novel scheme for quantum heat pumps powered by rapid time-periodic driving. We focus our investigation on a system consisting of two coupled driven quantum dots in contact with fermionic reservoirs at different temperatures. Such a configuration can be realized in a quantum-gas microscope. Theoretically we characterize the device by describing the coupling to the reservoirs using the Floquet-Born-Markov approximation.



Quantum Tunneling Showing Its Strength

Guohua Maier and Alejandro Saenz

Institut für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany

Some time ago a numerical approach had been implemented that describes two ultracold atoms in a finite optical lattice in full dimension and with realistic interatomic interaction potentials, for example a numerically given Born-Oppenheimer potential curve [1]. Even anisotropic dipole-dipole interactions were included [2]. For this purpose, configuration-interaction (CI), also known as exact diagonalization, was implemented using the uncoupled solutions of center-of-mass and relative-motion as a basis to form the configuration-state functions. This was extended to even solve the time-dependent Schrödinger equation for the case of an explicitly time-dependent trap potential [3]. In this work we adopted the code to investigate the dynamics of a weakly bound dimer in a single site of an optical lattice or in an optical microtrap, if the trap potential is changed in time, especially if it tilted. It is demonstrated that such a time-dependent tilt can be used to break an atomic dimer. In other words, the tunneling "force" is adopted for breaking a (chemical) bond. This may be used to either monitor very weak bond energies or to measure the corresponding magnetic field gradients (or other fields) that effectively lead to a tilt of the optical-lattice potential.

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(Machine) Learning to quickly swipe through a Quantum Phase Transition

F. Sauvage[1], U. Schneider[2] and F. Mintert[1]

[1] *Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
[2] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*

Ultra-cold atom setups provide a neat platform to study many-body systems with an unprecedented degree of control. In particular the dynamical tuning of control parameters can lead to the crossing of quantum phase transitions. A paradigm example is the realization of the superfluid to Mott insulator transition in an optical lattice by controlling the depth of the lattice potential [1]. Numerous new quantum phases have since been predicted and reaching them starting from easy to prepare initial state is of main interest.

Adiabatic manipulations (when possible) provide a straightforward way to realize such transitions but are experimentally limited by decoherence and noise accumulation. This motivates the design of fast (nonadiabatic) robust control protocols. Quantum optimal control deals with optimizing such protocols [2]. For complex dynamics, numerical simulations may not be accurate enough and it becomes necessary to perform optimizations with direct experimental feedback.

As a proof of concept we use machine learning inspired techniques to find the optimal driving of a finite 1D bosonic lattice from a superfluid to a Mott insulator phase (and vice-versa) close to the quantum speed limit. Optimizations are performed including realistic experimental characteristics such as noise and constraints in the control parameters, restricted access to experimental observables and limited numbers of simulations.

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Phase transition kinetics for a Bose Einstein condensate in a periodically driven band system

E. Michon[1], C. Cabrera-Gutiérrez[1], A. Fortun[1], M. Berger[1], M. Arnal[1], V. Brunaud[1], J. Billy[1], C. Petitjean[2], P. Schlagheck[2], and D. Guéry-Odelin[1]

[1] *Université de Toulouse; UPS; Laboratoire Collisions Agrégats Réactivité, IRSAMC; F-31062 Toulouse, France*

[2] *Département de Physique, CESAM research unit, University of Liege, B-4000 Liège, Belgium*

The dynamical transition of an atomic Bose–Einstein condensate from a spatially periodic state to a staggered state with alternating sign in its wavefunction is experimentally studied using a one-dimensional phase modulated optical lattice [1]. We observe the crossover from quantum to thermal fluctuations as the triggering mechanism for the nucleation of staggered states. In good quantitative agreement with numerical simulations based on the truncated Wigner method, we experimentally investigate how the nucleation time varies with the renormalized tunneling rate, the atomic density, and the driving frequency. The effective inverted energy band in the driven lattice is identified as the key ingredient which explains the emergence of gap solitons as observed in numerics and the possibility to nucleate staggered states from interband excitations as reported experimentally.

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Quantum Droplets with Tilted Dipoles

M. Schmitt[1] **and A. Pelster**[1]

[1]*Research Center OPTIMAS and Department of Physics,*
Technische Universität Kaiserslautern, Germany

Since 2005 there have been many striking advancements in Bose-Einstein condensates (BECs) with dipolar interactions [1-3], the most recent one being the discovery of quantum droplets, which are stabilized due to quantum fluctuations [4, 5]. With a variational approach we investigate the influence of a tilted dipole axis on quantum droplets in a wave guide-like setup [6]. At first we generalize for one quantum droplet the energy functional for the extended Gross-Pitaevskii theory [7-11] to tilted dipoles and determine the resulting deformation of the cloud as well as its stability as a function of the tilting angle. Furthermore, we consider two quantum droplets in a trap and calculate how their equilibrium distance depends on the tilting of the dipole axis. With this we gain new insight into the emergence of filaments of dipolar BECs, which was found for the untilted case experimentally [6] and numerically from solving the extended Gross-Pitaevskii equation [12].

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Experimental demonstration of Bose-Einstein condensation in the first excited band of the optical honeycomb lattice

Julius Seeger[1, *], Tobias Klafka[1], Alexander Ilin[1], Mario Neundorf[1], Klaus Sengstock[1], Juliette Simonet[1]

[1]Institut für Laserphysik, Universität Hamburg
Luruper Chaussee 149, 22761 Hamburg, Germany
** jseeger@physnet.uni-hamburg.de*

Bose-Einstein condensates in the ground state of optical lattices are widely used to emulate solid state systems, however orbital degrees of freedom are mostly unexplored. Condensates in excited bands extend the possibilities for quantum simulators of exotic solid state models such as engineering new topological phases. I will present the first realization of Bose condensed Rb-atoms in the second band of the hexagonal lattice with twofold atomic basis [1, 2]. We have studied the condensation process and the decay mechanisms. Our preparation technique allows us also to prepare the ultracold atoms in even higher bands, which builds a new platform for the quantum simulation with spinor condensates. I will report on the recent progress of this work.

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2d fermi gases under the microscope

Airlia Shaffer, C. Wilson, B. Mukherjee, P. Patel, Z. Yan, R. Fletcher, M. Zwierlein

[1]*Massachusetts Institute of Technology, Cambridge MA, USA*

Confining a quantum fluid in two dimensions (2D) profoundly changes its behavior and leads to a host of new phenomena, for example the possibility of topological superfluid transitions and quantum Hall states. Here we report our progress towards creating a uniform 2D fermionic gas of 6Li confined in a highly flexible optical potential. The homogenous density enables the study of physics typically difficult to access in harmonically trapped samples, such as critical phenomena, correlation functions, superfluid properties and the spectroscopic response. Incorporating a dual-objective high-resolution imaging system allows us to both manipulate and image the gas with sub-micron resolution, permitting the projection of tailored potentials and in situ imaging of topological defects.

How to dress radio-frequency photons with tunable momentum

B. Shteynas[1], J. Lee[1], F. Top[1], J.-R. Li[1], A. Jamison[1], G. Juzeliunas[2]

and W. Ketterle[1]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA
[2] Institute of Theoretical Physics and Astronomy, Vilnius, Lithuania

We demonstrate how the combination of oscillating magnetic forces and radio-frequency (RF) pulses endows RF photons with tunable momentum. The Floquet-engineered recoil kick in our experiment is 6 X 10^6 higher than usually negligible momentum of an RF photon. We observe velocity-selective spinflip transitions and the associated Doppler shift. This realizes the key component of purely magnetic spin-orbit coupling schemes for ultracold atoms, which does not involve optical transitions and therefore avoids the problem of heating due to spontaneous emission. The demonstrated scheme is conceptually very transparent and illustrates important elements of Floquet physics, as well as the role of mechanical and canonical momenta in implementing synthetic gauge fields.

Quantum Hall states of 2D Bose-Hubbard model and disorder

R. Bai[1,2], S. Bandyopadhyay[1,2], S. Pal[1], K. Suthar[1] and D. Angom[1]

[1]Physical Research Laboratory, Navarangpura, Ahmedabad 380009, India
[2] another Indian Institute of Technology Gandhinagar, Palaj, Gandhinagar 382355, India

We examine the existence of quantum Hall states in 2D Bose-Hubbard model in the presence of artificial gauge potential [1]. This is done using cluster mean field theory and exact diagonalization. We find that quantum Hall states are ground state for the 1/4 flux and filling factor of 1/2, 1, 3/2 and 2. For other combinations of flux and filling factor the competing superfluid state is the ground state. Introducing disorder modifies the phase diagram of the system in a dramatic way. There is a new phase, Bose glass, in the system and more importantly, the artificial gauge potential enlarge the Bose glass domain in the phase diagram [2].

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Material Mean-Field Equations for Photon Bose-Einstein Condensates

<u>E. Stein</u> and A. Pelster

Research Center OPTIMAS and Department of Physics,
Technische Universität Kaiserslautern, Germany
E-mail: estein@rhrk.uni-kl.de

In recent years the phenomenon of non-equilibrium Bose-Einstein condensation (BEC) has been studied extensively. One of the most recent and most prominent systems is a photon Bose-Einstein condensate [1]. The core of the system is a dye solution filling the microcavity in which the photons are harmonically trapped. Due to cyclic absorption and reemission processes of photons the dye leads to a thermalisation of the photon gas at room temperature. Furthermore, due to a non-ideal quantum efficiency, those cycles yield in addition a heating of the dye solution, which results in a change of the refractive index and, thus, in an effective photon-photon interaction [2].

In order to describe this thermo-optic effect at the mean-field level, we use an open-dissipative Schrödinger equation in which both the effect of the material degrees of freedom and the consequences of a slightly changing dye-solution temperature are explicitly taken into account. Furthermore, the temperature degree of freedom is described by a diffusion equation, which is coupled to the Schrödinger equation [3].

In this contribution we focus on discussing the influences of the material degrees of freedom on both the homogeneous photon BEC and the lowest-lying collective frequencies of the harmonically trapped photon BEC. The differences to the results of the corresponding analysis of a standard Gross-Pitaevskii equation are worked out within the realm of a linear stability analysis. In the trapped case we analyse, in particular, the violation of the Kohn theorem, i.e. the deviation of the dipole-mode frequency from the trap frequency [4,5], which arises from the temporal non-locality of the thermo-optic interaction.

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Quantum Scanning Microscope for Cold Atoms

D. Yang, D. V. Vasilyev, C. Laflamme, M. A. Baranov, and P. Zoller

Center for Quantum Physics, Faculty of Mathematics, Computer Science and Physics, University of Innsbruck, 6020 Innsbruck, Austria
Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria

We propose and analyze a scanning microscope to monitor "live" the quantum dynamics of cold atoms in a cavity QED setup. The microscope measures the atomic density with subwavelength resolution via dispersive couplings to a cavity and homodyne detection within the framework of continuous measurement theory. We analyze two modes of operation. First, for a fixed focal point the microscope records the wave packet dynamics of atoms with time resolution set by the cavity lifetime. Second, a spatial scan of the microscope acts to map out the spatial density of stationary quantum states. Remarkably, in the latter case, for a good cavity limit, the microscope becomes an effective quantum nondemolition device, such that the spatial distribution of motional eigenstates can be measured backaction free in single scans, as an emergent quantum nondemolition measurement.

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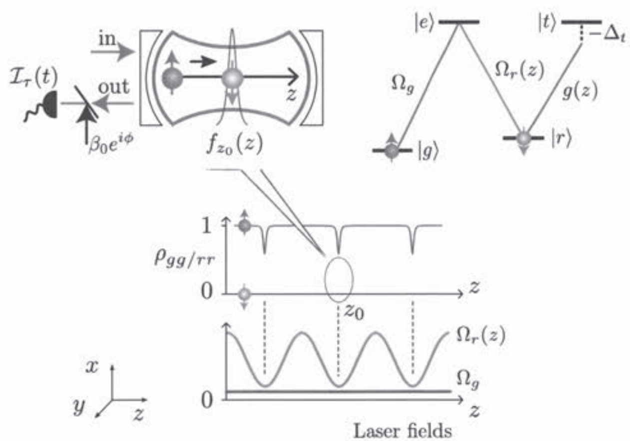

Stability diagram of degenerate Fermi gases of polar molecules with tilted dipoles

V. Veljić[1], **A. Pelster**[2], **and A. Balaž**[1]

[1] *Scientific Computing Laboratory, Center for the Study of Complex Systems, Institute of Physics Belgrade, University of Belgrade, Serbia*

[2] *Physics Department and Research Center OPTIMAS, Technical University of Kaiserslautern, Germany*

A recent experimental realization of an ultracold quantum degenerate gas of $^{40}K^{87}Rb$ molecules [1] opens up a new chapter in exploring strongly dipolar Fermi gases and many-body phenomena arising in that regime. This includes the deformation of the Fermi surface (FS) for polarized systems, where the electric dipoles have a preferential orientation, which can be achieved using an external field. Compared to atomic magnetic species [2,3], this effect is significantly increased in ultracold Fermi gases of polar molecules, and the stability of the system is expected to strongly depend on its geometry. Here we generalize a previous Hartree-Fock mean-field theory [2] for the Wigner function, which now takes into account that the cloud shape in the ground state is determined not only by the trap frequencies, but also by the dipoles' orientation. In the special case of a spherically symmetric trap, the cloud is elongated in the direction of the dipoles, similar to the FS. We obtain here a universal stability diagram for dipolar fermions and calculate the corresponding FS deformation for an arbitrary orientation of the dipoles, demonstrating the great promise for the exploration of degenerate molecules in electric fields, where the strong dipole-dipole interaction dominates. These results are important for designing future experiments with polar molecules, as well as for the interpretation of measured data, including the dynamics and the time-of-flight expansion.

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Effective Approach to Impurity Dynamics in One-Dimensional Trapped Bose Gases

S. I. Mistakidis[1], A. G. Volosniev[2], N. T. Zinner[3,4] and P. Schmelcher[1,5]

[1]Zentrum für Optische Quantentechnologien, Universität Hamburg, Hamburg, Germany
[2]Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
[3]Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark
[4]Aarhus Institute of Advanced Studies, Aarhus University, Aarhus, Denmark
[5]The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Hamburg, Germany

The low-energy dynamics of a mobile particle in a medium can often be described using the polaron quasiparticle: The impurity dressed by relevant collective excitations. It is a propitious time to study the polaron concept in degenerate Bose gases, because the current cold-atom laboratories provide a platform for testing theoretical calculations. In spite of the presence of some external confinement, the cold-atom experiments may even be used to test homogeneous polaron models. However, in this case the effect of the external trap must be thoroughly understood. Here we study such an effect in harmonically-trapped one-dimensional Bose gases. We show that, to describe an impurity in such inhomogeneous environments, one has to renormalize both the mass and the string constant – the classic renormalization of the mass alone is insufficient. We propose a one-body effective Hamiltonian that takes this into account, and use the multi-layer multi-configuration time-dependent Hartree method for bosons to test it. The numerical calculations show that the one-body description works well for the 'miscible phase' but must be modified for the 'immiscible phase'. Importantly, it turns out that the mass of the 'polaron' is smaller than the impurity mass, which means that it cannot straightforwardly be extracted from translationally-invariant models.

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Mapping a slow evolution onto a periodic driving of a Bose gas in the mean-field regime

E. Wamba, A. Pelster, and J.R. Anglin

Physics Department and Research Center OPTIMAS, Technische Universität Kaiserslautern, Germany

By using our recent results on the exact mappings between time evolutions of different quantum many-body systems [1], we construct a mean-field model of many-body systems with rapid periodic driving. The single-particle potential and the inter-particle interaction strength are both time-dependent at once, in a related way. We map the evolutions of the model system onto evolutions with slowly varying parameters. Such a mapping between a Floquet evolution and a static or slow process allows us to investigate non-equilibrium many-body dynamics and examine how rapidly driven systems may avoid heating up, at least when mean-field theory is still valid. From that special but interesting case, we learn that rapid periodic driving may not yield heating because the time evolution of the system has a kind of hidden adiabaticity, inasmuch as it can be mapped exactly onto that of an almost static system.

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Coherent Manipulation of Spin Correlations in the 2D Fermi Hubbard Model

N. Wurz[1], C. F. Chan[1], M. Gall[1], J. H. Drewes[1], E. Cocchi[1,2], L. A. Miller[1,2], D. Pertot[1], F. Brennecke[1] and M. Köhl[1]
[1]Physikalisches Institut, University of Bonn, Germany
[2] Cavendish Laboratory, University of Cambridge, United Kingdom
E-mail: nicola.wurz@uni-bonn.de

Quantum gases of interacting fermionic atoms in optical lattices promise to shed light on the low-temperature phases of Hubbard-type models, such as the anti-ferromagnet. We study the physics of the two-dimensional Hubbard model by loading a quantum degenerate two-component Fermi gas of 40K atoms into a three-dimensional optical lattice geometry with strongly suppressed tunneling along the vertical direction. Using high-resolution absorption imaging combined with radio-frequency spectroscopy we spin-selectively record the in-trap density distribution of singly occupied lattice sites in a single horizontal plane [1].

We coherently manipulate spin correlations within a plane using spatially and time-resolved Ramsey spectroscopy [2]. This novel technique allows us not only to imprint spin patterns but also to probe the static magnetic structure factor at arbitrary wave vector, in particular the staggered structure factor. From a measurement along the diagonal of the 1st Brillouin zone of the optical lattice, we determine the magnetic correlation length and the individual spatial spin correlators. At half filling, the staggered magnetic structure factor serves as a sensitive thermometer for the spin temperature, which we employ to study the thermalization of spin and density degrees of freedom during a slow quench of the lattice depth.

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Chern number spectrum of ultra-cold fermions in optical lattices as a function of independently tunable artificial magnetic, Zeeman and spin-orbit fields

Man Hon Yau[1] and C. A. R. Sá de Melo[1]
[1]Georgia Institute of Technology
Atlanta, GA 30332

In condensed matter physics, an external magnetic field couples with the charge and spin of electrons or holes, such that the orbital and Zeeman components are directly related and cannot be tuned independently. The Zeeman effect is so small that it is often treated a perturbation in comparison to the orbital effect for two-dimensional electronic systems in a lattice. As a consequence, the Chern number associated with the quantum hall conductance of an electronic system is basically determined by the strength of the orbital component, that is, the ratio Φ/Φ_0 of the unit cell magnetic flux Φ to the flux quantum Φ_0, and the filling factor ν. For instance, at flux ratio $\Phi/\Phi_0 = 1/3$, the only possible quantum Hall responses possess Chern numbers equal to -2 at ν = 2/3 and +2 at ν = 4/3, respectively. However, in ultra-cold atoms it is possible to create artificial magnetic, Zeeman and spin-orbit fields, which can be tuned independently. In our work, we describe ultra-cold fermions in two-dimensional square lattices at fixed flux ratios Φ/Φ_0, but varying Zeeman and spin-orbit fields [1] and we find that the spectrum of Chern numbers and quantum Hall conductances is much richer than in the corresponding problem of condensed matter physics. For instance, for the $\Phi/\Phi_0 = 1/3$ state, depending on the values of Zeeman and spin-orbit fields, the Chern number can take all integer values between -2 and 2 at a variety of filling factors ranging from 1/3 to 5/3 in steps of 1/3. This means that the Chern number spectrum and the quantum Hall conductance do not depend only on the ratio Φ/Φ_0 as is the case in condensed matter physics, but also on the Zeeman and spin-orbit fields. As a result, we derive a generalized Diophantine equation relating the Chern number, the flux ratio and the filling factor ν. Furthermore, we obtain a generalized bulk-edge correspondence by analyzing the equivalent open boundary problem in a strip geometry and relating the Chern number to the emergence of edge states of various chiralities as Zeeman and spin-orbit fields are varied.

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Quantum Simulation in Ultracold Quantum Gases of Alkaline-earth-like Atoms

Wei Zhang[1]

[1]Renmin University of China, Beijing, 100872 China

We discuss the quantum simulation of symmetry-protected topological (SPT) states for interacting fermions in quasi-one-dimensional gases of alkaline-earth-like atoms such as ^{173}Yb. Taking advantage of the separation of orbital and nuclear-spin degrees of freedom in these atoms, we consider Raman-assisted spin-orbit couplings in the clock states, which, together with the spin-exchange interactions in the clock-state manifolds, give rise to SPT states for interacting fermions. We then numerically map out the phase diagram, characterize the interaction-induced topological phase boundaries, and demonstrate the effects of bulk interactions on the topological properties of the system. The interaction-induced topological phase transition can be probed by measuring local density distribution of the topological edge modes.

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Measuring the topological phase transition via the single-particle density matrix

Jun-Hui Zheng[1], Bernhard Irsigler[1], Lijia Jiang[2], and Walter Hofstetter[1]

[1] *Institut für Theoretische Physik, Goethe-Universität, 60438 Frankfurt am Main, Germany*

[2] *Frankfurt Institute for Advanced Studies, 60438 Frankfurt am Main, Germany*

We discuss the topological phase transition of the experimentally realizable fermionic Haldane model with repulsive on-site interaction. We show that the Berry curvature of the topological Hamiltonian, the first Chern number, and the topological phase transition point can be extracted from the single-particle density matrix for this two-level interacting system. Furthermore, we design a scheme of holography for the single-particle density matrix of interacting fermionic systems in two-dimensional optical lattices exhibiting a two-sublattice structure.

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Realizing exotic quantum few-body states with strongly interacting systems in 1D

R.E. Barfknecht[1,2], S.E. Rasmussen[2], A. Foerster[1] and <u>N.T. Zinner[2,3]</u>

[1] *Instituto de Física da UFRGS, Av. Bento Gonçalves 9500, Porto Alegre, RS, Brazil*
[2] *Department of Physics and Astronomy, Aarhus University, Denmark*
[3] *Aarhus Institute of Advanced Studies, Aarhus University, Denmark*

Using the theory of strongly interacting 1D confined quantum systems, we will show new results on spin-charge separation for both two- and three-component systems [1]. Moreover, in the same setup an external drive applied to the internal states of the particles can give a subharmonic temporal response. This may help realize so-called discrete time crystals in few-body systems [2]. Lastly, we discuss new ideas on how to observe these states using current experimental techniques in ultracold atoms and superconducting quantum circuits.

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