Advances in Quantum Simulation and Sensing with Ultracold Gases

813. WE-Heraeus-Seminar

24 Jun - 28 Jun 2024
at the Physikzentrum Bad Honnef/Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
The Foundation is Germany's most important private institution funding physics.

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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 813. 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 an unprecedented high level of experimental control concerning all ingredients of the underlying many-body Hamiltonian. Therefore, ultracold gases are considered to be ideal quantum simulators, that is, they are best capable to simulate difficult problems in quantum many-body physics as they occur in condensed matter and other fields of physics.

In response to the occurrence of many new research directions in recent years, it is highly desirable to give a coherent overview over the diverse facets which are now appearing, and to reflect upon the future perspectives of the field. Thus, the seminar follows the interdisciplinary concept of bringing together experimental and theoretical scientists, who investigate the properties of ultracold quantum gases from different points of view, to exchange opinions, discuss problems, and disseminate new ideas. On the one hand, invited plenary talks by 25 selected leading international experts will guarantee a high scientific level for the seminar, and will provide its main backbone. On the other hand, all other participants will be given the opportunity to present their current research work within a high-class setting through shorter contributed talks or through posters, thereby generating a forum for identifying the most promising current trends and future perspectives.

Scientific Organizers:

PD Dr. Axel Pelster — RPTU Kaiserslautern-Landau, Germany
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Introduction

Administrative Organization:

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Registration:

Martina Albert (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h)
and Monday (08:00 – 12:30 h)

Program

Sunday, June 23, 2024

17:00 – 21:00	Registration	
18:00 – 21:00	*BUFFETT SUPPER / Informal get together*	
21:00 –	*Switzerland-Germany (2024 UEFA European Football Championship)*	

Monday, June 24, 2024

07:40 – 08:40	*BREAKFAST*	
08:40 – 09:00	Carlos Sá de Melo	**Opening and welcome**

Session 1: Quantum Sensing I

09:00 – 09:45	Alice Sinatra	**Nonlocal correlations and sensing with cold atoms in optical lattices**
09:45 – 10:30	Li You	**Quantum enhanced sensing with spinor atomic condensates in linear and nonlinear interferometries**
10:30 – 11:00	*COFFEE BREAK*	

Session 2: Quantum Simulation I

11:00 – 11:45	Yoshiro Takahashi	**Quantum simulation and sensing with ultracold ytterbium atoms**
11:45 – 12:30	Zhen-Sheng Yuan	**Microscopic study on simulating lattice gauge theory with ultracold atoms**
12:30 – 14:00	*LUNCH*	

Program

Monday, June 24, 2024

Session 3: Contributed Talks I

14:00 – 14:30	Andrea Bergschneider	**Enhancing pair tunneling with Floquet engineering**
14:30 – 15:00	Johannes Hofmann	**Scale and conformal invariance in rotating few-fermion systems**
15:00 – 15:30	Aurélien Fabre	**Universal self-organization dynamics in strongly-interacting fermions with long-range photon-mediated interactions**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

16:15 – 18:45 **Plenary Poster Flash Presentations**

18:45 – 20:15 *HERAEUS DINNER at the Physikzentrum*
(cold and warm buffet, with complimentary drinks)

20:15 – 21:45 **Poster Session I**

Program

Tuesday, June 25, 2024

08:00 – 09:00	*BREAKFAST*	

Session 4: Quantum Sensing II

09:00 – 09:45	Kai Bongs	**Disruptive applications enabled by quantum sensors and clocks**
09:45 – 10:30	Susanne Yelin	**Sensing and QED with cooperative atom arrays**
10:30 – 11:00	*COFFEE BREAK*	

Session 5: Different Dimensions

11:00 – 11:45	Henning Moritz	**Fermionic superfluids in two and three dimensions**
11:45 – 12:30	Franco Dalfovo	**BEC and BKT transitions in a Bose gas in the 2D-3D dimensional crossover**
12:30 – 14:00	*LUNCH*	

Session 6: Molecules

14:00 – 14:45	Andreas Schindewolf	**From microwave shielding to field-linked molecules**
14:45 – 15:30	Sebastian Will	**Creating and exploring Bose-Einstein condensates of dipolar molecules**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 17:00	**Group Discussions I**	
17:00 – 18:30	**Poster Session II**	
18:30 – 20:00	*DINNER*	
20:00 –	**Socializing**	

Program

Wednesday, June 26, 2024

08:00 – 09:00	*BREAKFAST*	

Session 7: Rydberg Atoms

09:00 – 09:45	Florian Meinert	**Circular Rydberg atoms for quantum simulations**
09:45 – 10:30	Michael Fleischhauer	**Non-equilibrium physics with Rydberg atoms: Epidemic dynamics, self-organized criticality and anomalous directed percolation**
10:30 – 11:00	*COFFEE BREAK*	

Session 8: Vortices

11:00 – 11:45	Andrea Richaud	**Inertial effects in superfluid vortex dynamics**
11:45 – 12:30	Giacomo Roati	**Vortex matter in strongly-correlated superfluids**
12:30 – 14:00	*LUNCH*	
14:00 – 14:10	**Conference photo** (in front of the main entrance)	
14:10 – 18:30	**Excursion** **Leisurely hike to the Drachenfels (Dragon's rock)**	
18:30 – 20:00	*DINNER*	

Evening Talk

20:00 – 21:00	Masahito Ueda	**Beyond-hermitian quantum physics**

21:00 –	**Socializing**	

Program

Thursday, June 27, 2024

08:00 – 09:00	*BREAKFAST*	

Session 9: Light and Matter

09:00 – 09:45	Corinna Kollath	**Controlling the dynamics of atomic correlations via the coupling to a dissipative cavity**
09:45 – 10:30	Thomas Pohl	**Quantum states of light from lattices of ultracold**
10:30 – 11:00	*COFFEE BREAK*	

Session 10: Fermions

11:00 – 11:45	Joseph Thywissen	**Emergent s-wave interactions between identical fermions via orbital-singlet pair wavefunctions**
11:45 – 12:30	Tarik Yefsah	**Quantum gas microscopy of fermionic matter in continuous space**
12:30 – 14:00	*LUNCH*	

Session 11: Quantum Simulation II

14:00 – 14:45	Markus Greiner (remote access)	**Hubbard quantum simulations - from dipolar quantum solids to kinetic magnetism**
14:45 – 15:30	Selim Jochim	**How close is 42 to infinity?**
15:30 – 16:00	*COFFEE BREAK*	

Program

Thursday, June 27, 2024

Session 12: Contributed Talks II

16:00 – 16:30	Niels Kjaergaard	**Rydberg atomic polarimetry of THz fields**
16:30 – 17:00	Rukmani Bai	**Miscible-immiscible transition in the strongly interacting bosonic mixtures**
17:00 – 17:30	Hans Keßler	**Route to chaos in an atom-cavity system**
17:30 – 18:30	**Group Discussions II**	
18:30 – 20:00	*DINNER*	
20:00 – 21:30	**Poster Session III**	

Program

Friday, June 28, 2024

08:00 – 09:00	*BREAKFAST*	

Session 13: Non-Equilibrium Dynamics

09:00 – 09:45	Lucia Hackermüller	**Non-equilibrium molecule association as a shortcut to adiabaticity and 3D-printing for quantum technologies**
09:45 – 10:30	Matthias Weidemüller	**Rydberg spin glas**
10:30 – 11:00	*COFFEE BREAK*	

Session 14: Quantum Simulation III

11:00 – 11:45	Robert Smith	**Explorations with Erbium**
11:45 – 12:30	Hendrik Weimer	**Quantum simulation of open quantum systems**
12:30 – 12:40	Axel Pelster	**Poster Awards and Concluding Remarks**
12:40 – 14:00	*LUNCH*	

End of seminar and departure

Posters

Posters

1 Session 1	Bar Alluf	Duality breaking, mobility edges, and the connection between topological Aubry–André and quantum Hall insulators in atomic wires with fermions
2 Session 2	Antun Balaz	Effects of quantum depletion and gradient corrections on the critical atom number of dipolar droplets
3 Session 3	Søren Balling	Impurity physics with Bose-Einstein condensates
4 Session 1	Soumik Bandyopadhyay	Simulating holographic matter with cold atoms in optical cavity
5 Session 2	Alice Bellettini	Rotational states of an asymmetric vortex pair with mass imbalance in binary condensates
6 Session 3	Abdelaali Boudjemaa	Quantum temperature sensing of ultralow temperature in biwire polar molecules
7 Session 1	Sandra Brandstetter	Observation of real space pairing in a strongly correlated few-fermion system
8 Session 2	Domantas Burba	Strong long-range interactions and geometrical frustration in subwavelength Raman lattices
9 Session 3	Raja Chamakhi Bouras	Coherent transport of Bose-Einstein condensates in asymmetric moving optical lattices
10 Session 1	Jie Chen	Entanglement and correlations induced by dynamical quantum phase transitions
11 Session 2	Sayan Choudhury	AA counter-diabatic route to realize dynamical many-body freezing in the periodically driven Lipkin-Meshkov-Glick model

Posters

12 Session 3	Tim de Jongh	Quantum gas microscopy of a continuous Fermi gas at zero temperature
13 Session 1	Sudipta Dhar	Many-body physics with ultracold atoms: From Bethe strings to anyons in one dimension
14 Session 2	Andrea Di Carli	Quantum simulation with Erbium atoms in optical-tweezer arrays
15 Session 3	Harry Donegan	Subradiant excitations in atomic arrays with twisted light
16 Session 1	Maxim Efremov	Angular Bloch oscillations and their applications
17 Session 2	Karthik Eswaran	Wannier states in photonic time crystals
18 Session 3	Andrea Fantini	Programmable quantum simulator with Strontium Rydberg atoms in optical tweezer arrays
19 Session 1	Julian Feß	Indication of critical scaling in time during the relaxation of an open quantum system
20 Session 2	Arnaldo Gammal	Faraday waves driven by Rabi oscillations on a bubble Bose-Einstein condensed mixture
~~21~~ ~~Session 3~~	(cancelled)	
22 Session 1	Hari Sadhan Ghosh	Rotation-induced supersolidity of a dipolar Bose-Einstein condensate confined in a bubble trap
23 Session 2	Alexander Guthmann	Engineering floquet-feshbach resonances
24 Session 3	Nikolai Kaschewski	Non-perturbative corrections to the weakly interacting two component Fermi gas

Posters

~~25~~ ~~Session 1~~	(cancelled)	
26 Session 2	**Nils Krause**	**Energy damping of a Jones-Roberts soliton: analytic and numerical results**
27 Session 3	**Milan Krstajic**	**Measuring the dipolar interaction shift of the BEC critical temperature**
28 Session 1	**Chang Chi Kwong**	**Synthetic gauge fields in the tripod and double tripod systems**
29 Session 2	**Maria Lanaro**	**Emergence of orbital physics with ultracold bosons in the BBH model**
30 Session 3	**Simon Lepleux**	**Study of vortices interaction and solitons in a quantum fluid of light**
31 Session 1	**Lucas Levrouw**	**Vortex dynamics in Fermi superfluids across the BEC-BCS crossover**
32 Session 2	**Denis Mujo**	**Collective oscillation modes of dipolar quantum droplets**
33 Session 3	**Axel Pelster**	**Projection optimization method for open-dissipative quantum fluids and its application to a single vortex in a photon Bose-Einstein condensate**
34 Session 1	**Thomas Picot**	**Quantum simulations with an atomic tweezer array strongly coupled to a Fiber Fabry-Perot Cavity**
35 Session 2	**Sayak Ray**	**Temporal bistability in the dissipative Dicke-Bose-Hubbard system**
36 Session 3	**Alejandro Saenz**	**Inelastic confinement induced resonances: tool or limitation for quantum sensing and simulation?**

Posters

37 Session 1	Seongho Shin	Estimating the magnitude of the homogeneous perturbations by measuring the number of BEC molecules in ultracold chemical reactions
38 Session 2	Andrei Sidorov	Towards discrete time crystals with bouncing Bose-Einstein condensates
39 Session 3	Tomasz Sowinski	Correlations of strongly interacting ultra-cold p-wave fermions in one-dimensional trap
40 Session 1	Binhan Tang	Bogoliubov theory of 1D anyons in a lattice
41 Session 2	Roberto Tricarico	Localization phenomenon in Rydberg-gadget networks
42 Session 3	Clemens Ulm	Exploring supersolidity of dipolar quantum gases: vortex formation and neutron star analogues
43 Session 1	Jasper van de Kraats	Non-equilibrium dynamics of strongly interacting Bose-Fermi mixtures
44 Session 2	Gokul Vengillasery Illam	Cavity-based non-destructive detection in ultracold gases
45 Session 3	Kobe Vergaerde	Engineering Hamiltonians in the lab
46 Session 1	Joris Verstraten	Single-Atom-Resolved fluctuation thermometry of quasi-2D Fermi gases in continuous space
47 Session 2	Claudia Volk	Direct cooling of dipolar molecules towards Bose-Einstein condensation
48 Session 3	Etienne Wamba	Simulating a periodic driving with a sudden quench in an ultra cold quantum gas
49 Session 1	Xiao Wang	Floquet Schrieffer-Wolff transform based on Sylvester equations

50 Session 2	Alexander Wolf	Solitons on the surface of a sphere
51 Session 3	Sejung Yong	Unravelling interaction and temperature contributions in unpolarized trapped fermionic atoms in the BCS regime
52 Session 1	Emi Yukawa	Generating entangled helical spin currents in a spinor Bose-Einstein condensate
53 Session 2	Jin Zhang	A rapid fermionic quantum simulator for random unitary observables

Abstracts of Lectures

(in alphabetical order)

Miscible-Immiscible Transition In The Strongly Interacting Bosonic Mixtures

Rukmani Bai[1] and Soumik Bandyopadhyay[2,3]

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[2] Pitaevskii BEC Center, CNR-INO and Department of Physics, University of Trento, Via Sommarive 14, Trento, I-38123, Italy
[3]INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Trento, Italy

Interaction plays key role in the mixing properties of a multi-component system. It is now well established that the miscibility-immiscibility transition (MIT) in a weakly interacting mixture of Bose gases is predominantly determined by the strengths of the intra and inter-component two-body contact interactions, range of which is usually restricted to individual sites of a lattice system. On the other hand, in the strongly interacting regime other interaction induced processes become relevant, which can influence properties of the system in addition to stabilizing new quantum phases.

In this talk, I will present our recent results on the MIT in the strongly interacting phases of two-component bosonic mixture trapped in a homogeneous two-dimensional square optical lattice. Particularly, we investigate the transition when both the components are in superfluid, one-body staggered superfluid or super solid phases. Our study prevails that, similar to the contact interactions, the MIT can be steered by competing intra and inter-component density-induced tunnelings and off-site interactions. To probe the MIT in the strongly interacting regime we study the extended version of the Bose-Hubbard model with the density induced tunneling and nearest-neighboring interaction terms, and focus in the regime where the hopping processes are considerably weaker than the onsite interaction.

References

[1] R. Bai and S. Bandyopadhyay, **arxiv: 2403.14601**

Enhancing pair tunneling with Floquet engineering

A. Bergschneider[1], N. Klemmer[1], J. Fleper[1], V. Jonas[1], A. Sheikhan[1], C. Kollath[1] and M. Köhl[1]

[1]*Physikalisches Institut, University of Bonn, 53115 Bonn, Germany*

The Hubbard model has been very successful in describing quantum phases that emerge from the interplay of single-particle tunneling and on-site interaction. Its lack of explicit pair tunneling terms, however, makes the quantum simulation of various predicted quantum phases inaccessible.

We utilize Floquet engineering in chains of double wells to implement effectively interacting systems that show a crossover from explicit density-assistant to pair tunneling [1]. Exploring the effective parameters, we additionally observe an enhancement of pair tunneling amplitude beyond the effective superexchange of its undriven counterpart. These findings may bring the realization of novel quantum phases based on pairing mechanisms more within reach.

References

[1] Klemmer, N., Fleper, J., Jonas, V., Sheikhan, A., Kollath, C., Köhl, M., and Bergschneider, A., *Floquet-driven crossover from density-assisted tunneling to enhanced pair tunneling,* arXiv 2404.08482

Disruptive applications enabled by quantum sensors and clocks

K. Bongs

Institute of Quantum Technologies, German Aerospace Center, Wilhelm-Runge Straße 10, 89081 Ulm, Germany

The ability to manipulate quantum systems at the single particle level has created unprecedented opportunities for the development of new technologies. While quantum computers need sophisticated shielding from the environment, in order to maintain coherence in quantum superpositions, quantum sensors transform this vice into a virtue and use these systems for precise measurements. As a consequence, quantum sensors and also clocks are already maturing out of laboratories and into real world applications [1]. In this talk, I will present some of the recent developments and future application opportunities involving these early quantum technologies. A particular outlook will investigate possible applications in Space, improving navigation and the management of Space assets.

References

[1] Kai Bongs, Simon Bennett & Anke Lohmann, Nature, Vol 617, 673 (2023).

BEC and BKT transitions in a Bose gas in the 2D-3D dimensional crossover

N.A. Keepfer[1,2], I.-K Liu[1], N.P. Proukakis[1], and F. Dalfovo[2]

[1]Joint Quantum Centre (JQC) Durham-Newcastle, School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne, UK
[2] Pitaevskii INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento,Trento, Italy

The equilibrium properties of a weakly interacting atomic Bose gas across the Berezinskii-Kosterlitz-Thouless (BKT) and Bose-Einstein condensation (BEC) phase transitions are numerically investigated through a dimensionality crossover from two to three dimensions. The crossover is realized by confining the gas in an experimentally feasible hybridized trap which provides homogeneity along the planar xy directions through a box potential in tandem with a harmonic transverse potential along the transverse z direction. The dimensionality is modified by varying the frequency of the harmonic trap from tight to loose transverse trapping. Our findings, based on a stochastic (projected) Gross-Pitaevskii equation, showcase a continuous shift in the character of the phase transition from BKT to BEC, and a monotonic increase of the identified critical temperature as a function of dimensionality, with the strongest variation exhibited for small chemical potential values up to approximately twice the transverse confining potential.

Reference

[1] N. A. Keepfer, I.-K. Liu, F. Dalfovo, and N. P. Proukakis, Phys. Rev. Research **4**, 033130 (2022)

Universal self-organization dynamics in strongly-interacting fermions with long-range photon-mediated interactions

A. Fabre[1], T. Zwettler[1], G. Del Pace[1], T. Bühler[1], G. Bolognini[1], S. Chattopadhyay[2], F. Marijanovic[2], L. Skolc[2], E. Demler[2], C. Halati[3], T. Giamarchi[3], S. Ushino[4] and J.-P. Brantut[1]

[1] *Ecole Polytechnique Fédérale de Lausanne, Institute of Physics, Lausanne, Switzerland*
[2] *Institute for Theoretical Physics, ETH Zürich, Zürich, Switzerland*
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[4] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Japan*

Non-equilibrium dynamics through phase transitions remain an open problem in strongly-interacting quantum systems. While phase transitions with local interactions have been largely studied both theoretically and experimentally, little is known about instabilities in Fermi gases originating from long-range interactions, which compete with Pauli exclusion principle and short-range contact interactions.

Here we investigate the dynamics of a unitary Fermi gas undergoing a phase transition with density-wave ordering induced by long-range photon-mediated interactions in a high-finesse optical cavity. We observe in real-time the exponential rise of the order parameter following an instantaneous quench and track the evolution of its time scale over three orders of magnitude as the system is quenched deeper above the critical point. Remarkably, this time scale is independent of the strength of contact interactions from the ideal up to the unitary limit, and can be orders of magnitude faster than the Fermi time, which we attribute to sum-rules constraints on the response function of the system. We also show that the universal character further extends to the response to linear ramps of finite speeds.

Our study establishes long-range interacting Fermi gases as a new, separate universality class of dynamical instabilities and provides a striking example of simple, universal dynamics emerging in far from equilibrium, strongly-interacting systems.

WE-Hereaus June 2024

Non-equilibrium physics with Rydberg atoms: Epidemic dynamics, self-organized criticality and anomalous directed percolation

Michael Fleischhauer

RPTU, University of Kaiserslautern-Landau, Germany

In nature there is a striking abundance of scale invariance, ranging form the distribution of earthquakes or forest fires to the dynamics of epidemics or the spread of news in social media. The origin of this is believed to be a phenomenon called self-organized criticality (SOC), a mechanisms where due to dissipation a many-body system dynamically evolves by itself to the critical point of a phase transition without the need of parameter fine-tuning.

The spread of excitations caused by Rydberg facilitation in a gas of laser-driven atoms is an ideal model system for studying such dynamics. In Rydberg facilitation atoms are laser-coupled off-resonantly to a Rydberg state which leads to very rare excitation events. Atoms in a particular distance of an already excited Rydberg atom can however rapidly be excited since the dipole interaction shifts them into resonance. Thus an initial seed can cause a rapid cascade of excitations. Controlled by the density of atoms and the driving strength, the system displays an absorbing-state phase transition between an active and an absorbing phase, believed to be of directed-percolation (DP) universality. Furthermore decay from the Rydberg state to auxiliary "inert" levels provides a loss channel causing the system to self-organize to the critical state when starting in the active phase. Since this dissipation is strongly reduced once the critical point is reached, further evolution into the absorbing phase happens only on much longer time scales. Despite their importance, the unambiguous experimental observation of self-organized criticality and DP universality remains challenging and has only been achieved in few systems in the last years. Recent experiments on Rydberg facilitation have provided evidence of SOC, showing however critical exponents between the DP value and mean-field behaviour. Based on extended Monte-Carlo simulations supported by Machine Learning algorithms, I will show that the facilitation dynamics in a gas of atoms is very complex due to an effective network structure of ground-state atoms and the temperature of the gas. For a frozen gas, ground state atoms in the facilitation distance form an Erdös Renyi network, which for increasing temperatures crosses over into a dynamical network eventually approaching the mean-field regime. If the Erdös Renyi network is below the percolation threshold, the critical point of the absorbing-state phase transition is replaced by an extended heterogeneous Griffith phase, characterized by generic scale invariance but lack of universality. Above the percolation threshold the absorbing-state phase transition is of DP universality in the frozen gas. Atomic motion associated with a non-vanishing temperature changes this behaviour substantially. I will show that high gas temperatures lead to a power-law- or Levy-flight- tail of the distribution of facilitation distances. This changes the DP universal behavior to *anomalous* directed percolation with temperature-dependent universal critical exponents, consistent with the experimental findings.

Hubbard Quantum Simulations - from Dipolar Quantum Solids to Kinetic Magnetism

Markus Greiner

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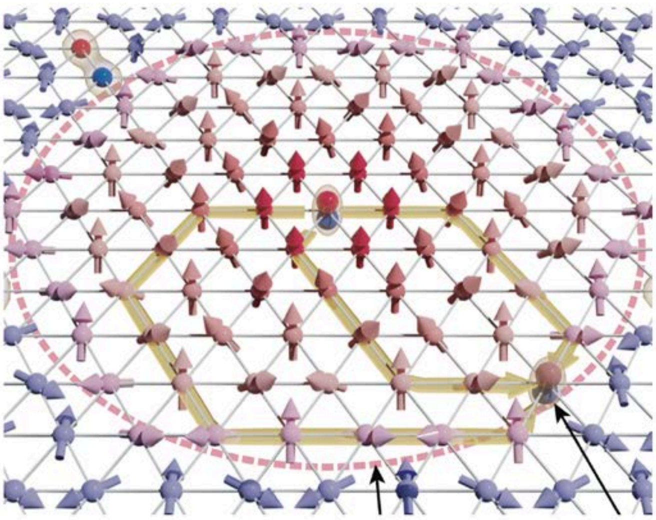

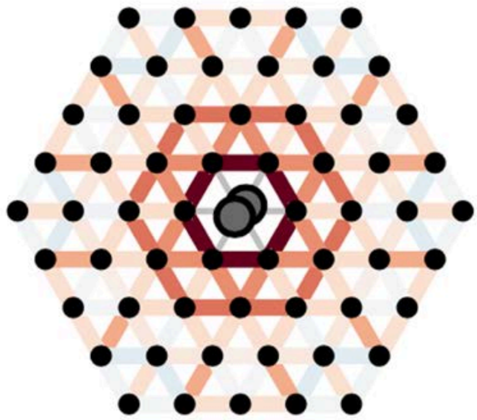

Quantum simulations with ultracold atoms in optical lattices enter the next phase, in which we can extend bosonic and fermionic Hubbard models in a wide range of ways. Using magnetic long-ragne interacations we realize strongly correlated dipolar quantum gases in a Hubbard lattice and observe quantum-phase transitions to stripe and checkerboard phases. In our Fermi-Hubbard system we are making progress on lowering temperatures and observe Nagaoka Ferromagnetism, a surprising realization of kinetic magnetism, emerging as we introduce geometric spin frustration in a triangular Fermi-Hubbard lattice. We use floquet engineering to further extend the programmability of Hubbard simulators.

Non-equilibrium molecule association as a shortcut to adiabaticity and 3D-printing for quantum technologies

L. Hackermueller[1]

[1]*School of Physics, University of Nottingham, Nottingham, United Kingdom*

We study non-equilibrium association of Li_2 Feshbach molecules over a range of temperatures $T \gg T_F$ to $T \ll T_F$. We observe an enhancement of the atom–molecule coupling efficiency as the fermionic atoms reach degeneracy demonstrating the importance of many-body coherence not captured by the conventional LZ model [1]. Based on this, we develop a theoretical model that can explain the temperature dependence of the atom–molecule coupling and use it to demonstrate a shortcut to adiabaticity in molecular association efficiency.

I will also report on our recent results of a new type of microscopic atom-photon interface [2]. Hybrid quantum devices, incorporating both atoms and photons, are able to exploit the benefits of both systems. In our system, atoms are first cooled in a magneto-optical trap, transferred to an optical dipole trap, and positioned inside a transverse, 30 µm diameter through-hole in an optical waveguide, created via laser micromachining. We discuss precise atom number detection, precision spectroscopy and photon storage. An adaptive Bayesian optimisation method allows us to demonstrate an advantage of estimating a measurement parameter.

For portable quantum devices additive manufacturing or 3D-printing offers unique advantages. We have demonstrated a full magneto-optical trapping setup based on additive manufacturing techniques including a printed ultra-high vacuum chamber. Freedom of design enables remarkably compact and resilient systems and allows weight reduction of more than 70% [3]. I will discuss a proposal to use such a system, where walls can be built to create dedicated boundary conditions, to detect the effect of dark domain walls related to dark energy and dark matter. [4]
We have extended this method to transparent glass elements and will report on the first 3D-printed vapour cells. Going beyond freedom of design, these can offer integrated printed detectors and gold nanoparticles and pave the way to ultra-compact sensors.

References

[1] V. Naniyil et al., New J. Phys. **24**, 113005 (2022)
[2] E. da Ros et al., Phys. Rev. Res. **2**, 033098 (2020)
[3] S. Madkhaly et al., PRX Quantum **2**, 030326 (2021)
[4] K. Clements et al., arXiv:2308.01179 (2024)

Scale and conformal invariance in rotating few-fermion systems

V. Bekassy[1] and <u>J. Hofmann[2]</u>

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[3] *Nordita, Stockholm University and KTH Royal Institute of Technology, 10691 Stockholm, Sweden*

We show that rotating two-dimensional Fermi gases possess a nonrelativistic scale and conformal invariance at weak interactions, where the scale invariance of universal short-range interactions is not broken by quantum effects. We demonstrate the symmetry in the excitation spectrum of few-fermion ensembles in a harmonic trap obtained by exact diagonalization, which are constrained by the operator-state correspondence. The excitation spectrum is shown to split in a set of primary states, the energies of which correspond to scaling dimensions of conformal operators, and derived excited states that consist of breathing modes as well as two different center-of-mass excitations, which describe cyclotron and guiding-center excitations of the total particle cloud. Furthermore, the conformal symmetry is manifest in the many-body wave function, where it dictates the form of the hyperradial component, which we demonstrate using Monte Carlo sampling of few-body wave functions. We argue that these results are testable in current experiments on mesoscopic Fermi gases.

References

[1] V. Bekassy and J. Hofmann, Phys. Rev. Lett. **128**, 193401 (2022).

[2] V. Bekassy and J. Hofmann, arXiv:2310.12216 (2023).

How close is 42 to infinity?

Selim Jochim

Heidelberg University, Physikalisches Institut, Heidelberg, Germany

For many phenomena that occur in Nature, a successful description commonly involves taking the limit of a continuum, i. e. an infinite system size.
It is our quest to understand how such a continuum emerges from a finite system size, where access to single particle resolved quantities is still available.

In terms of energy, this involves the competition of three scales:
a) The interaction strength between atoms, that can be tuned using a Feshbach resonance
b) The finite energy gap between single particle states or energy shells stemming from the confinement,
c) The Fermi energy, controlled by the number of fermionic atoms is the scale driving the convergence of observables to the continuum limit

In our experiments we harmonically trap a fixed number of atoms in two dimensions, with the largest number to date being 42 fermionic atoms. This corresponds to six shells being filled, with the Fermi energy significantly surpassing the shell spacing.
Our tunable platform allows us to manipulate such systems with an extreme fidelity. As one example we can control the (relative) angular momentum between two single atoms in such a configuration, allowing us to prepare a microscopic Laughlin wave function.

Route to chaos in an atom-cavity system

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In driven non-linear systems, various kinds of bifurcations can be observed on their route to chaos. From the evolution of Floquet multipliers one can extract information which serves as a precursor for phase transitions and dynamical instabilities. This method is applied in classical non-linear physics, for example, to obtain early warning signals.
Utilising our impressive control over an atom-cavity platform, we are able to prepare our system in various dynamical regimes and study the bifurcation experimentally in a quantum gas to obtain insights that could potentially be applied to more complex systems.
We prepare a Bose-Einstein condensate inside the centre of a cavity and pumping it perpendicular to the cavity axis with a standing wave light field. Upon crossing a critical pump strength, we observe a pitchfork phase transition from a normal to a steady state self-organized phase [1]. Employing an open three- level Dicke model, this transition can be understood as a transition between two fixpoints, indicating a pitchfork bifurcation. If the pump strength is increased further, the system undergoes a Hopf bifurcation. This causes limit cycles, which have time crystalline properties, to emerge [2]. In this regime, our model no longer shows fixpoints but stable attractive periodic orbits [3]. For strong pumping, we observe a second bifurcation, in our case a Neimark-Sacker bifurcation. Its main characteristics is an oscillation with two incommensurate frequencies, this may indicate the formation of a continuous time quasicrystal [4]. Finally, in the regime of very strong pumping, we observe chaotic dynamics with many contributing frequencies.

References

[1] J. Klinder, et al., PNAS 112, 11 (2015)
[2] P. Kongkhambut, et al., Science 307 (2022)
[3] J. Skulte, et al., arXiv:2401.05332 (2023)
[4] P. Kongkhambut, et al., manuscript in preparation

Rydberg atomic polarimetry of THz fields

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RF field sensing based on Rydberg-excited atoms in vapour cells has received immense interest over the past decade [1]. By probing the Rydberg atomic medium optically through electromagnetically-induced transparency (EIT), an RF electric field matching the transition between two Rydberg states reveals itself as an Autler-Townes splitting of the EIT signal. We have previously capitalized on this effect to implement an optical antenna for communication [2] and a standalone vapour cell transducer for distant field sensing [3].

Here we explore polarization spectroscopy of a linearly polarized THz field. We recently established S ↔ P Rydberg transitions as ideally suited for polarization-insensitive electrometry [4]: when rotating the RF field polarization, the split EIT spectrum remains invariant. In contrast, the use of $D_{3/2} \leftrightarrow P_{1/2}$ and $D_{5/2} \leftrightarrow P_{1/2}$ Rydberg transitions yields polarization imprints on the EIT signal. Moreover, these two cases exhibit a compelling complementarity: for a resonant EIT coupling field, the detected probe fields will oscillate out of phase for a scanned THz polarization. This is akin to the outputs of the two ports of a polarization beam splitter and as such our scheme implements balanced THz polarimeter.

References

[1] J. Sedlacek, A. Schwettmann, H. Kübler, R. Lõw, T. Pfau and J. Shaffer, Microwave electrometry with Rydberg atoms in a vapour cell using bright atomic resonances, Nat. Phys. **8**, 819 (2012)

[2] A. B. Deb and N. Kjærgaard, Radio-over-fiber using an optical antenna based on Rydberg states of atoms, Appl. Phys. Lett. **112**, 211106 (2018)

[3] J. S. Otto, M. Chilcott, A. B. Deb, and N. Kjærgaard, Distant RF field sensing with a passive Rydberg-atomic transducer, Appl. Phys. Lett. **123**, 144003 (2023)

[4] M. Cloutman, M. Chillcott, A. Elliott, J.S. Otto, A.B. Deb, N. Kjærgaard, Polarization-insensitive microwave electrometry using Rydberg atoms, Phys. Rev. Appl. **21**, 044025 (2024)

Controlling the dynamics of atomic correlations via the coupling to a dissipative cavity

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Quantum gases in optical cavities have shown many exciting phenomena as the self-organization into superradiant phases. Additionally many complex phases have been predicted to be realizable in these systems reaching from topologically interesting phases to glass like phases. The theoretical treatment of these systems is very difficult due to the presence of the long range coupling of the cavity to the atoms. We investigate the full quantum evolution of ultracold interacting bosonic atoms on a chain and coupled to an optical cavity. Extending the time-dependent matrix product state techniques and the many-body adiabatic elimination technique to capture the global coupling to the cavity mode and the open nature of the cavity, we examine the long time behavior of the system beyond the mean-field elimination of the cavity field. We show that the coupling to the cavity enables the control of the dynamics of the correlation and can lead to a self-organized collapse and revival dynamics.

Circular Rydberg atoms for quantum simulations

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I will present our work on a novel Rydberg qubit encoded in circular states of strontium atoms in optical tweezers. Circular Rydberg states promise orders-of-magnitude longer lifetimes compared to their low-L counterparts, which allows for overcoming fundamental limitations in the coherence properties of Rydberg atom based quantum simulators. We have recently demonstrated efficient transfer into high-n circular Rydberg atoms with n=79 via rapid adiabatic passage, implemented a qubit between circular states of closeby hydrogenic manifolds coupled via a two-photon microwave transition, and showed trapping of the circular state enabled via the second available valence electron of the Sr atom [1]. These results open exciting prospects for exploiting unique properties of long-lived circular states of two-valence electron atoms for quantum technologies, comprising coherent ionic core manipulation. In the second part of the talk, I will discuss our endeavor to realize a gate-based quantum computer using a novel fine-structure qubit encoded in the metastable $^3P_0$ and $^3P_2$ states of strontium [2]. We have recently implemented this qubit for the first time and measured its coherence in a magic optical tweezer, which is enabled by tuning the tensor polarizability of the $^3P_2$ via a control magnetic field.

References

[1] C. Hölzl et al., Phys. Rev. X 14, 021024 (2024)
[2] G. Unnikrishnan et al., Phys. Rev. Lett. 132, 150606 (2024)

Fermionic superfluids in two and three dimensions

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In this talk, I will review our recent work on superfluidity in homogeneous 2D and 3D Fermi gases. In the first part I will report measurements of the dynamic structure factor of 2D [1,2] and 3D [3] superfluids. Using Bragg spectroscopy, we determine the critical velocity and the superfluid gap in the crossover from Bardeen-Cooper-Schrieffer (BCS) pairing to Bose-Einstein condensation (BEC) of molecules, allowing for detailed comparisons with and benchmarks for theory. Our measurements enable us to directly study the role of reduced dimensionality on strongly correlated superfluids.

In the second part I will present recent measurements in which we investigate how strong confinement modifies the excitations of the superfluid order parameter, namely the Bogoliubov and amplitude modes. When performing trap modulation spectroscopy in a highly oblate ultracold Fermi gas, we unexpectedly observe a well-defined collective mode throughout the entire BEC-BCS crossover. In excellent agreement with an effective field theory we interpret the results as an observation of a Higgs mode in the BCS regime, i.e. an oscillation of the amplitude of the order parameter, which hybridizes with and ultimately fully transforms into a spatial excitation of the order parameter along the confined direction.

References

[1] L. Sobirey et al., Science **372**, 844 (2021)
[2] L. Sobirey et al., Phys. Rev. Lett. **129**, 083601 (2022)
[3] H. Biss et al., Phys. Rev. Lett. **128**, 100401 (2022)

Quantum states of light from lattices of ultracold atoms

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Coupling atoms and photons in optical resonators provides an attractive approach to generating effective atomic interactions, suggesting a versatile toolbox for quantum simulations of long-range interacting systems. Conversely, ultracold atoms in optical lattice have recently emerged as an interesting free-space interfaces for coherent atom-photon coupling with a high degree of control over collective light-matter scattering. This talk will present a simple diagrammatic description which offers intuitive insights into nonlinear optical processes that can occur in such atomic metasurfaces. By considering multiple layers as few-atom resonators, it will further be shown how the interplay between collective light-matter coupling, atomic interactions and geometry can generate distinctly different kinds of effective photon-photon interactions. We will outline prospects of realizing photonic quantum gases or fluids with controllable photon-photon interactions and discuss potential applications from photonic quantum logic to quantum enhanced imaging at the wavelength scale.

Inertial effects in superfluid vortex dynamics

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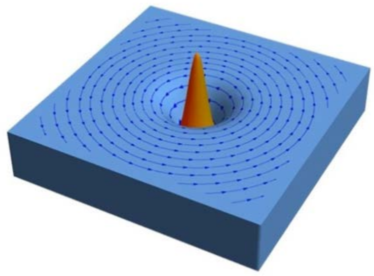
In quantum matter, vortices are topological excitations characterized by quantized circulation of the velocity field. They are often modeled as funnel-like holes around which the quantum fluid exhibits a swirling flow. In this perspective, vortex cores are nothing more than empty regions where the superfluid density goes to zero.



In the last few years, this simple view has been challenged and it is now increasingly clear that, in many real systems, vortex cores are not that empty: thermal atoms, quasi-particle excitations, tracer atoms, just to name a few examples, can be commonly found in the cores of quantum vortices. These particles provide the vortex with an effective inertial mass.

In this talk, I will discuss the dynamics of two-dimensional point-like vortices whose cores are filled by massive particles. I will show that the introduction of core mass in the standard point-vortex model constitutes a *singular perturbation*, as it alters the order of the equations of motion. I will also discuss the new dynamical regimes that are unlocked by the presence of core mass. The simplest example is a single vortex within a rigid circular boundary, where a massless vortex can only precess uniformly. In contrast, the presence of a massive core can lead to small-amplitude radial oscillations, which are, in turn, clear signatures of the associated inertial effect.

I will also show that, as opposed to their massless counterpart, massive vortices can collide, resulting into vortex/antivortex annihilation processes or into the stabilization of doubly charged vortices. Eventually, I will discuss how the collective properties of a many-vortex system are modified by the presence of core mass. More specifically, I will show that the superfluid Kelvin-Helmholtz instability, governing the breakdown of regular vortex arrays, is mitigated by the inertial effects.

References

[1] A. Richaud, V. Penna, R. Mayol, and M. Guilleumas, Phys. Rev. A **101**, 013630 (2020)
[2] A. Richaud, V. Penna, and A. L. Fetter, Phys. Rev. A **103**, 023311 (2021)
[3] A. Richaud, G. Lamporesi, M. Capone, and A. Recati, Phys. Rev. A **107**, 053317 (2023)
[4] M. Caldara, A. Richaud, M. Capone, P. Massignan, arXiv:2403.11987

Vortex matter in strongly-correlated superfluids

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Topological defects play a crucial role in shaping the properties and structures of various out-of-equilibrium physical and biological systems across a broad spectrum of scales. These systems range from planetary atmospheres and turbulent flows in classical and quantum fluids to the electrical signaling in excitable biological media [1]. In superfluids and superconductors, the motion of quantized vortices is linked to the onset of dissipation, which limits the superflow [2]. Comprehending vortex dynamics poses a significant challenge due to the intricate interplay among vortices, disorder, and system dimensionality.

We tackle this challenge by investigating vortex matter in planar homogeneous Fermi superfluids [3]. By engineering vortex configurations and monitoring their evolution through tracking vortex trajectories, we gain unparalleled control over vortex dynamics. This capability transforms our system into an ideal "quantum laboratory" for unraveling the fundamental nature of vortex-driven instabilities and dissipation [4,5]. Our research opens prospects for understanding vortex-matter phenomena in strongly correlated superfluids.

References

[1] Spiral and Vortices, K. Tsuji and S. C.Müller Editors, Springer Nature Switzerland AG (2019)

[2] B. I. Halperin, G. Refael and E. Demler, Int. J. Mod. Phys, **B 24**, 20n21 (2010)

[3] W. J. Kwon et al., Nature, **600** (2021)

[4] D. Hernandez-Rajkov et al., Nature Physics in press (2024)

[5] N. Grani et al., in preparation

From microwave shielding to field-linked molecules

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The long-range anisotropic interactions of dipolar molecules, as well as their numerous internal degrees of freedom make them a very versatile and promising platform for quantum simulation. However, for a long time, the formation of degenerate gases of dipolar molecules was stifled by inelastic interactions at short range [1]. We recently demonstrated that a method called 'microwave shielding' can be used to overcome this challenge [2]. At far long range, the molecules interact via dipole moments induced by a near-resonant microwave field. Molecules attracting each other eventually reach a distance at which their dipole-dipole interaction dominates over the coupling to the microwave field. The molecules are then transferred adiabatically to a state with repulsive interaction, which prevents them from undergoing an inelastic collision at short range. The resulting interaction potential well can support bound states, which had been predicted 20 years ago as so-called 'field-linked' states [3]. Emerging from the interaction potential these states give rise to field-linked resonances, which can be used to tune the contact interaction of the molecules independent of their dipole-dipole interaction [4]. By ramping over such a resonance, we managed to populate the meta-stable field-linked state coherently [5]. Microwave shielding and the understanding of field-linked states have recently enabled the first BEC of chemically bound molecules [6]. In the future field-linked states might give rise to novel supersolid phases, *p*-wave superfluidity and potentially provide a pathway to ultracold metal clusters.

[1] R. Bause *et al.*, J. Phys. Chem. A **127**, 729 (2023)
[2] A. Schindewolf *et al.*, Nature **607**, 677 (2022)
[3] A. V. Avdeenkov and J. Bohn, Phys. Rev. Lett. **90**, 043006 (2003)
[4] X.-Y. Chen, A. Schindewolf, *et al.*, Nature **614**, 614 (2023)
[5] X.-Y. Chen *et al.*, Nature **626**, 283 (2024)
[6] N. Bigagli *et al.*, arXiv:2312.10965

Nonlocal Correlations and Sensing with Cold Atoms in Optical Lattices

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We consider a physical platform consisting of two-level atoms in an optical lattice in a squeezed-Mott configuration, where the atoms, spatially distributed in different modes, share internal state correlations (spin squeezing). We first focus on the case where the spins can be locally flipped, but all measurements are collective. We show that squeezing or over-squeezing leads to significant quantum gain in multi-parameter estimation, imaging and compressed sensing. In the second part of the talk, I will hypothesize that both local spin manipulation and local measurements are possible, and I will study the violation of Bell's inequalities in this system, including the possibility of having some empty or doubly occupied sites, e.g. due to finite temperature effects, while raising the lattice to obtain the squeezed-Mott state from an initial two-component Bose-Einstein condensate.

References

1. D. Kajtoch, E. Witkowska, A. Sinatra, Europhys. Lett. **123**, 20012 (2018).
2. Y. Baamara, M.Gesner, A.Sinatra, SciPost Physics **14**, 050 (2023).
3. Y. Baamara, T. Hernandez, A. Sinatra, E. Witkowska, in preparation

Explorations with Erbium

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<u>R. P. Smith</u>[1]

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My talk will consist of two parts.

First, I will present our measurements of the modification of transition temperature for Bose Einstein Condensation (BEC) due to dipole-dipole interactions. The effect of dipolar interactions on harmonically trapped BECs has been the subject of intense and fruitful research over recent years, but despite being theoretically calculated over 15 years ago [1] the modification of the BEC transition temperature due to dipole-dipole interactions has, up to now, not been experimentally observed. We use an ultracold erbium gas confined in a highly prolate trap to directly observe the dependence of the critical temperature on the orientation of the dipoles relative to the trap and compare the results with theoretical expectations.

Second, I will discuss the challenges and progress towards, the realization of a box-trapped dipolar gas.

References

[1] Phys. Rev. Lett. **98**, 080407 (2007)

Quantum simulation and sensing with ultracold ytterbium atoms

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A system of ultracold atoms in an optical lattice is an ideal quantum simulator of a strongly-correlated quantum many- and few-body systems as well as a quantum sensor for new physics beyond the Standard Model. Ultracold ytterbium (Yb) offers unique possibilities in these studies owing to the several unique features. In this talk, I will report our recent experiments of quantum simulation and quantum sensing using ultracold Yb in an optical lattice.

One of the unique properties of ytterbium atoms is the existence of ultranarrow optical transtions between the ground and metastable states, offering the high-resolution probing of quantum few-body systems realized in an optical lattice. By combing the inter-orbital Feshbach resonance with occupancy-resolved laser spectroscopy, we reveal the behaviors of effective multi-body forces in a strongly-interacting regime and, in particular, we find the evidence of novel effective four-body force with an 2-sigma significance [1]. These results will benchmark theory of strongly-interacting few-body quantum systems.

In addition, a rich variety of isotopes offers the novel possibility of searching for a new hypothetical particle mediating a force between an electron and a neutron, through high-resolution isotope-shift measurements. Our quantum sensor consisting of ultracold bosonic Yb atoms in a magic-wavelegnth lattice is proven to be so sensitive to the new particle that we can set a stringent limit for the new particle [2,3].

Other studies in our lab such as an Yb atom tweezer array and quantum thermalization will be also reported.

References

[1] K. Honda *et al,* arXiv:2402.16254.
[2] K. Ono et *al,* Phys. Rev. X **12**, 021033 (2022).
[3] T. Ishiyama *et* al, Phys. Rev. Lett. **130**, 153402 (2023)

Emergent s-wave interactions between identical fermions via orbital-singlet pair wavefunctions

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Ultracold gases in highly anisotropic confining potentials often occupy the lowest motional state of the strongly confined directions. This configuration has led to a wealth of low-dimensional physics, well described by quasi-one-dimensional (q1D) or quasi-two-dimensional (q2D) models. A generalized scenario includes *orbital* excitations: quanta of motional excitation in the strongly confined directions. Here we demonstrate how activation of an orbital degree of freedom enables effective s-wave interactions between spin-polarized fermionic potassium atoms in q1D and in q2D. The short-range interaction is tuned through a p-wave Feshbach resonance. The paradoxical emergence of exchange-symmetric interactions between identical fermions is explained by the orbital-singlet pair wavefunctions. We anticipate that this mechanism generalizes to other scenarios, for example, emergent p-wave interactions in spin-polarized bosonic systems with underlying d-wave interactions.

Beyond-Hermitian Quantum Physics

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The Yang-Lee edge singularity is a quintessential nonunitary critical phenomenon characterized by anomalous scaling. However, an imaginary magnetic field involved in this phenomenon makes its physical implementation highly nontrivial. We invoke the quantum-classical correspondence and quantum measurement to physically realize the nonunitary quantum criticality in an open quantum system [1]. In particular, we show that the essential singularity in the superconducting gap is directly related to the number of Yang-Lee zeros which are distributed on a semicircle in the complex plane of the interaction strength due to the Fermi-surface instability. We also present photonic experiments to directly measure the partition function and the Yang-Lee zeros, where unconventional scaling laws for finite-temperature quantum dynamics are observed and agree with our theory predictions [3].

References

[1] N. Matsumoto, M. Nakagawa, and M. Ueda, Phys. Rev. Res. **4**, 033250 (2022).
[2] H. Li, X.-H. Yu, M. Nakawaga, and M. Ueda, Phys. Rev. Lett. **131**, 216001 (2023).
[3] H. Gao, K. Wang, L. Xiao, M. Nakagawa, N. Matsumoto, D. Qu, H. Lin, M. Ueda, and P. Xue, arXiv:2312.01706.

Rydberg Spin Glas

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Using our Rydberg platform as a quantum simulator for disordered Heisenberg systems [1], we have found signatures indicating that an isolated frozen gas of quantum spins under dipolar interactions shows similar features as a "classical" spin glass [2]. The relaxation of the magnetization after a quench follows a stretched-exponential function, which appears to be universal in the sense that it is independent on the degree of disorder [3] and the symmetries of the underlying Heisenberg Hamiltonian [4]. We observe a drastic change in the late-time magnetization when increasing disorder strength. The data is well described by models based on pairs of strongly interacting spins, which are treated as thermal for weak disorder and isolated for strong disorder. Our results indicate a crossover into a pair-localized prethermal regime in a closed quantum system of thousands of spins [5]. Most recently, we observed linear response to an external effective magnetic field indicating non-thermal behavior. Measurements of the magnetic susceptibilities as a function of the energy in the system show the existence of two regimes with different magnetic behavior. The lower energy regime exhibits pronounced hysteresis, which might indicate the existence of a glas-phase transition [6].

* Work done in collaboration with Gerhard Zürn, Eduard Braun, Sebastian Geier, Titus Franz (now at Max-Planck Institute for Quantum Optics), Valentina Salazar Silva, Annika Tebben, Adrian Brämer und Martin Gärttner (now at Universität Jena)

References

[1] A. Piñeiro Orioli *et al.*, PRL **120**, 063601 (2018); S. Geier, N. Thaicharoen, C. Hainaut *et al*., Science **374**, 1149 (2021); P. Scholl, H. J. Williams , G. Bonet *et al*., PRX Quantum **2**, 020303 (2022).

[2] P. Schultzen, T. Franz *et al.,* Phys. Rev. B **105**, L020201 (2022); P. Schultzen, T. Franz *et al.,* Phys. Rev. B **105**, L100201 (2022).

[3] A. Signoles, T. Franz *et al*., PRX **11**, 11011 (2021).

[4] T. Franz *et al.*, arXiv:2209.08080 (2022).

[5] T. Franz, S. Geier *et al*., arXiv:2207.14216 (2022).

[6] M. Hornung, E. Braun *et al.*, in preparation.

Quantum simulation of open quantum systems

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Using quantum computers to simulate open quantum many-body systems is one of the most promising areas to observe a quantum advantage over classical simulation methods [1]. One especially exciting case is the quantum contact process [2], which can be seen as a quantum version of an epidemic and where numerical results point to a novel universality class driven by quantum fluctuations. I report on our latest results on large-scale classical simulations of variants of the quantum contact process and discuss their relevance to current experiments in trapped-ion quantum computers.

References

[1] H. Weimer, Nature Phys. **19**, 1753 (2023)
[2] F. Carollo et al., Phys. Rev. Lett. **123**, 100604 (2019)

Creating and exploring Bose-Einstein condensates of dipolar molecules

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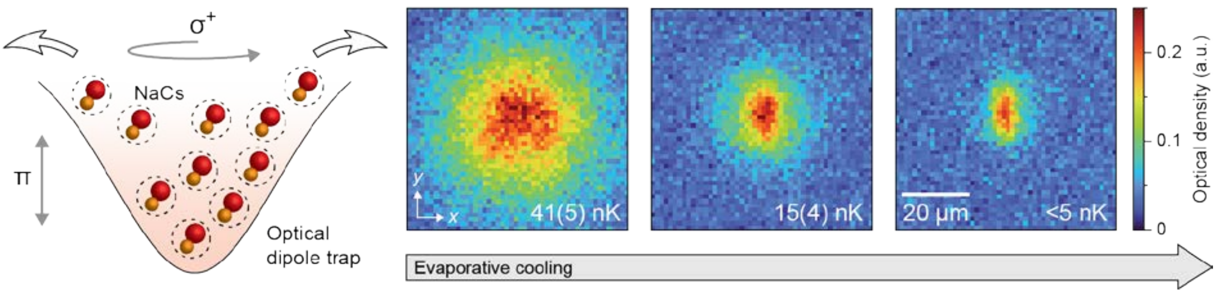
We have recently created the first Bose-Einstein condensate (BEC) of dipolar molecules [1-4]. We efficiently cool sodium-cesium molecules from 700 nK to less than 10 nK, deep into the quantum degenerate regime. The lifetime of the molecular BEC is longer than one second, reaching a level of stability similar to ultracold atomic gases. A cornerstone of this advance is double microwave shielding, a novel technique that gives us control over intermolecular interactions and reduces inelastic loss of molecules by four orders of magnitude. The creation of a BEC constitutes the first observation of a phase transition in an ultracold molecular gas.

In this talk, I will discuss our experimental approach, share latest insights, and give an outlook on opportunities with our system for many-body quantum physics, quantum simulation and quantum information. Thanks to a large dipole moment, BECs of sodium-cesium molecules promise access to regimes of dipolar quantum matter that have been inaccessible so far.



References

[1] Bigagli, Yuan, Zhang, et al., Observation of Bose-Einstein condensation of dipolar molecules, arXiv:2312.10965 (2023) (in print)

[2] Bigagli, et al., Collisionally stable gas of bosonic dipolar ground state molecules, Nature Physics, **19**, 1579-1584 (2023)

[3] Stevenson, et al., Ultracold gas of dipolar NaCs ground state molecules, Phys. Rev. Lett. **130**, 113003 (2023)

[4] Warner, et al., Overlapping Bose-Einstein condensates of Na and Cs, Phys. Rev. A **104**, 033302 (2021)

Quantum Gas Microscopy of Fermionic Matter in Continuous Space

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Quantum gas microscopy has emerged in the last decade as a powerful technique to probe and manipulate quantum many-body systems at the single-atom level. So far, however, it has only been used to the study of lattice and spin chain physics, prominently to explore the Hubbard model and its generalizations. In this talk, I will present our recent efforts to extend quantum gas microscopy to the study of fermionic many-body systems in continuous space and characterize them at a previously inaccessible levels of resolution and control.

Firstly, I will show its use to image the in-situ density probability of deterministically prepared single-atom wave packets as they expand in a plane, and how we obtain a crucial benchmark for the reliability of our imaging protocol [1]. Secondly, I will report on quantum gas microscopy of a quasi-2D ideal Fermi gas, where we measure spatially-resolved density correlation functions of the second and third order, and reveal their temperature dependence. From the same samples, we also extract the number fluctuations in small subsystems of the cloud where zero temperature quantum fluctuations play an important role, leading to a significant deviation from the behavior predicted by the fluctuation-dissipation theorem in the thermodynamic limit. Our ability to distinguish the quantum and the thermal fluctuations contributions, allows us to perform accurate fluctuation-thermometry over a large dynamical range, from nearly zero temperature to several Fermi temperatures. These results represent the first application of quantum gas microscopy to continuous-space many-body systems. Our approach offers radically new possibilities for the exploration of strongly interacting Fermi gases at the single-atom level.

References

[1] J. Verstraten, K. Dai, M. Dixmerias, B. Peaudecerf, T. de Jongh, and T. Yefsah, **arXiv:2404.05699** (2024)

Sensing and QED with cooperative atom arrays

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The physics of cooperative atoms in ordered arrays is dominated by two properties: first, a strongly frequency-selective reflectivity and second, the ability to confine polariton modes cleanly within the structure. This makes such a system highly sensitive to and controllable by light fields and allows to treat it similar to a cavity for impurities. Among the applications of such systems are metrology and biologically inspired transport processes.

Quantum enhanced sensing with spinor atomic condensates in linear and nonlinear interferometries

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Statistical inference of a parameter based on measurements from an ensemble of uncorrelated particles is lower bounded by the classical precision limit or the standard quantum limit (SQL). Quantum entangled ensembles can beat SQL. Several paradigms for such enhanced interferometry will be discussed and demonstrative experiments with spinor atomic Bose-Einstein condensates based on work from our group over the past few years will be summarized. Squeezed states of condensed atoms are deterministically generated and applied in linear interferometry [1,2,3]; time-reversed evolutions of squeezing or un-squeezing are implemented for nonlinear interferometry to preferentially amplify signal over noise [4,5,6]; both illustrating quantum enhanced precisions.

This series of work was carried out with students, postdocs, and other collaborators, including Drs. Xin-Yu Luo, Meng Khoon Tey, Yi-Quan Zou, Ling-Na Wu, Qi Liu, Shuai-Feng Guo, Jia-Hao Cao, Feng Chen, Xin-Wei Li, Ming Xue, Jun-Jie Chen, Tian-Wei Mao, Wen-Xin Xu, and Yi-Xiao Huang.

References

[1] Xin-Yu Luo, Yi-Quan Zou, Ling-Na Wu, Qi Liu, Ming-Fei Han, Meng Khoon Tey, and L. You, "Deterministic entanglement generation from driving through quantum phase transitions," Science **355**, 620 (2017).

[2] Yi-Quan Zou, Ling-Na Wu, Qi Liu, Xin-Yu Luo, Shuai-Feng Guo, Jia-Hao Cao, Meng Khoon Tey, and Li You, "Beating the classical precision limit with spin-1 Dicke state of more than 10,000 atoms," PNAS **115**, 6381 (2018).

[3] Shuai-Feng Guo, Feng Chen, Qi Liu, Ming Xue, Jun-Jie Chen, Jia-Hao~Cao, Tian-Wei Mao, Meng-Khoon Tey, and Li You, "Faster State Preparation across Quantum Phase Transition Assisted by Reinforcement Learning," Phys. Rev. Lett. **126**, 060401 (2021).

[4] Qi Liu, Ling-Na Wu, Jia-Hao Cao, Tian-Wei Mao, Xin-Wei Li, Shuai-Feng Guo, Meng Khoon Tey, and Li You, "Nonlinear interferometry beyond classical limit enabled by cyclic dynamics," Nature Physics **18**, 167-171 (2022).

[5] Tian-Wei Mao, Qi Liu, Xin-Wei Li, Jia-Hao Cao, Feng Chen, Wen-Xin Xu, Meng Khoon Tey, Yi-Xiao Huang, and Li You, "Quantum enhanced sensing by echoing spin-nematic squeezing in atomic Bose-Einstein condensate," Nature Physics **19**, 1585-1590 (2023).

[6] Jia-Hao Cao, Feng Chen, Qi Liu, Tian-Wei Mao, Wen-Xin Xu, Ling-Na Wu, and Li You, "Detection of entangled states supported by reinforcement learning," Phys. Rev. Lett. **131**, 073201 (2023).

Microscopic study on simulating lattice gauge theory with ultracold atoms

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Exploring the fundamental structure and basic laws of the universe constitutes an essential drive to physicists. Along with the achievements in laser cooling and implementation of Bose-Einstein condensate and quantum phase transitions in optical lattices, ultracold atoms become a unique system for quantum computation/ simulation and precision measurement. We study strongly correlated synthetic quantum material with microscopic techniques for solving formidable tasks to the state-of-the-art supercomputers. I will introduce our recent research on one of such synthetic quantum material, the lattice gauge theory (LGT). We implemented a U(1) LGT Hamiltonian with ultracold atoms trapped in optical lattices and studied the relevant properties of thermalization dynamics and quantum criticality [1-6].

References

[1] Han-Ning Dai et al. Four-body ring-exchange interactions and anyonic statistics within a minimal toric-code Hamiltonian. Nature Physics **13**, 1195 (2017).

[2] Bing Yang et al. Observation of gauge invariance in a 71-site Bose-Hubbard quantum simulator. Nature **587**, 392 (2020).

[3] Zhao-Yu Zhou et al. Thermalization dynamics of a gauge theory on a quantum simulator. Science **377**, 311 (2022).

[4] Guo-Xian Su et al. Observation of many-body scarring in a Bose-Hubbard quantum simulator. Phys. Rev. Res. **5**, 023010 (2023).

[5] Han-Yi Wang et al. Interrelated thermalization and quantum criticality in a lattice gauge simulator, Phys. Rev. Lett. **131**, 050401 (2023).

[6] Wei-Yong Zhang et al. Observation of microscopic confinement dynamics by a tunable topological angle, arXiv:2306.11794.

Abstracts of Posters

(in alphabetical order)

Duality breaking, mobility edges, and the connection between topological Aubry–André and quantum Hall insulators in atomic wires with fermions

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It is well known that the Aubry-André model lacks mobility edges due to its energy-independent self-duality but may exhibit edge states.
When duality is broken, we show that mobility regions arise and non-trivial topological phases emerge.
By varying the degree of duality breaking, we identify mobility regions and establish a connection between Aubry-André atomic wires with fermions and quantum Hall systems for a family of Hamiltonians that depends on the relative phase of laser fields, viewed as a synthetic dimension.
Depending on the filling factor and the degree of duality breaking, we find three classes of non-trivial phases: conventional topological insulator, conventional topological Aubry-André insulator, and unconventional (hybrid) topological Aubry-André insulator.

References

[1] Alluf, B., & Melo, C. (2023). Controlling Anderson localization of a Bose-Einstein condensate via spin-orbit coupling and Rabi fields in bichromatic lattices. *Phys. Rev. A, 107, 033312.*

Effects of quantum depletion and gradient corrections on the critical atom number of dipolar droplets

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The first experimental realization of quantum droplets in dipolar condensates [1] has highlighted the importance of quantum fluctuations [2,3], which were later shown to be the main source of system's stability against the dipolar collapse. The droplets were predicted and shown to be self-bound beyond the critical atom number even without the trap. However, there is a systematic difference in theoretical estimates of the critical atom number and experimental results [4]. Here we use an approach based on the extended Gross-Pitaevskii equation, which includes quantum depletion and beyond-LDA gradient corrections, to numerically and variationally study their effects on the critical atom number.

References

[1] H. Kadau et al., Nature **530**, 194 (2016).
[2] A. R. P. Lima and A. Pelster, Phys. Rev. A **84**, 041604(R) (2011).
[3] A. R. P. Lima and A. Pelster Phys. Rev. A **86**, 063609 (2012).
[4] F. Böttcher et al., Phys. Rev. Research **1**, 033088 (2019).

Impurity physics with Bose-Einstein condensates

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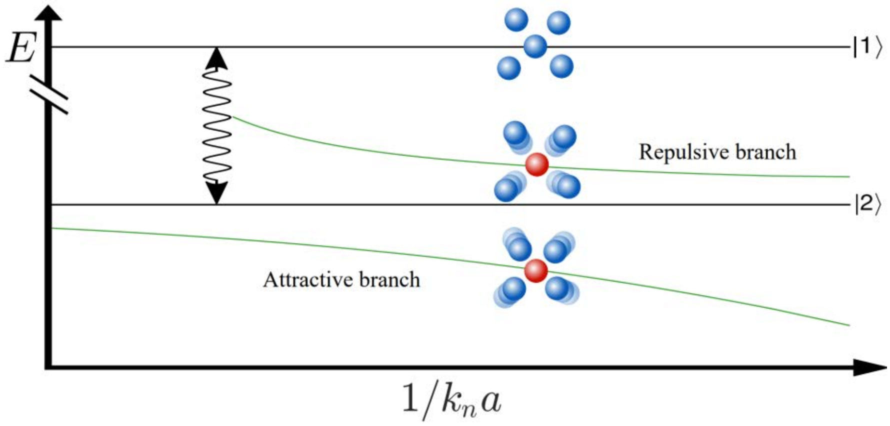

An impurity particle embedded in a bosonic environment poses a fundamental quantum many-body problem. The impurity, effectively described as a quasiparticle called the Bose polaron, is dressed by the surrounding medium. The polaron picture was originally introduced to understand interactions between electrons and atoms in solids. However, in this setting, densities are so high that the dynamics occur on a timescale that is not experimentally resolvable. We use Bose-Einstein condensates, where densities are comparably much lower, to quantum simulate impurity physics. We use a combination of spectroscopic and interferometric schemes to investigate the spectral and dynamical properties of the Bose polaron.

We utilize an interferometric Ramsey-like method to investigate the non-equilibrium dynamics in ^{39}K Bose-Einstein condensates, letting a different Zeeman state act as an impurity embedded within. This experimental scheme grants access to the quantum coherence of the impurity state, and we can resolve the ultrafast dynamics. Due to the rich Feshbach structure in ^{39}K, we can tune the coupling between medium and impurity – both for attractive and repulsive interactions.

In earlier experiments, we have extensively investigated the dynamics of the impurity state in the regime, where the interaction between medium and impurity is attractive [1,2]. Recently, we have extended these investigations to repulsive interactions, where the energy landscape is richer [3]. Interestingly, we observe quantum beating between competing polaronic states, and we demonstrate that the energy difference between these states can be extracted from the quantum beat frequency.

[1] M.G. Skou et al., Nat. Phys. 17, 731–735 (2021)
[2] M.G. Skou et al., Phys. Rev. Research 4, 043093 (2022)
[3] A.M. Morgen et al., arXiv:2310.18183

Simulating holographic matter with cold atoms in optical cavity

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The quest for a quantum theory of gravity has led to the discovery of quantum many-body systems that are dual to gravitational models with quantum characteristics. Amongst these the Sachdev-Ye-Kitaev (SYK) model has received tremendous research interest in recent years. The model features maximal scrambling of quantum information, and opens a potential inroad to experimentally investigating aspects of quantum gravity. A scalable laboratory realisation of this model, however, remains outstanding.

In this presentation, we shall be discussing a possible implementation of the SYK model in cavity quantum electrodynamics platforms [1]. Our detailed analytical and numerical analysis reveals that a cloud of fermionic atoms trapped in a multi-mode optical cavity subjected to a spatially disordered AC-Stark shift [2] retrieves the physics of the SYK model, with random all-to-all interactions and fast scrambling. Furthermore, our work demonstrates that for local observables the out-of-equilibrium dynamics of the model is universal with respect to generic initial conditions [3]. To reveal this, we develop a general open quantum system frame-work for the disorder averaged closed evolution, and reveal the universality through the spectral characteristics of the corresponding Liouvillian [3, 4]. In the non-Hermitian settings, the model clearly satisfies the markers of the Eigenstate Thermalization Hypothesis (ETH), demonstrating the applicability of ETH in chaotic non-Hermitian systems [5].

Our works provide a blueprint for realising the SYK model in a scalable system, with the prospect of studying holographic quantum matter in the laboratory, and shed light on challenging questions for systems far from equilibrium, such as, thermalization of closed and open disordered quantum systems.

References

[1] P. Uhrich, S. Bandyopadhyay, N. Sauerwein, J. Sonner, J.-P. Brantut, P. Hauke arXiv:2303.11343 (2023).

[2] N. Sauerwein, F. Orsi, P. Uhrich, S. Bandyopadhyay, F. Mattiotti, T. Cantat-Moltrecht, G. Pupillo, P. Hauke, J.-P. Brantut, Nature Physics 19, 1128-1134 (2023).

[3] S. Bandyopadhyay, P. Uhrich, A. Paviglianiti, P. Hauke, Quantum 7, 1022 (2023).

[4] A. Paviglianiti, S. Bandyopadhyay, P. Uhrich, P. Hauke, *J. HEP* 2023, 126 (2023).

[5] S. S. Roy, S. Bandyopadhyay, R. C. de Almeida, P. Hauke, arXiv:2309.00049 (2023).

Rotational states of an asymmetric vortex pair with mass imbalance in binary condensates

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We consider massive vortices in binary condensates, where the immiscibility condition entails the trapping of the minority component in the vortex cores of the majority component. We study such vortices by means of a 2D point-like model, and show how the relevant dynamical equations exhibit vortex-pair solutions characterized by different vortex masses and circular orbits of different radii *a* and *b* ("CO solutions"). These solutions are validated by the simulations of the Gross-Pitaevskii equations for binary condensates (**Fig. 1**). After examining the properties of the vortex-pair rotational frequency Ω as a function of the vortex masses for a given pair geometry, we define the rotational-state diagram $\mathcal{D}$ (**Fig. 2**), describing all the possible vortex-pair solutions in terms of the orbit radii at given Ω. This includes solutions with equal-mass pairs but $a \neq b$ or with one of the two masses (or both) equal to zero. Also, we analytically find the minimum value of Ω for the existence of such solutions, and obtain numerically the critical frequency Ω_c below which $\mathcal{D}$ changes its structure and the transition to an unstable vortex-pair regime takes place. Our work highlights an indirect measurement scheme to infer the vortex masses from the orbits radii *a* and *b*, and a link between the vortex masses and the vortex-pair small-oscillation properties (see **Fig. 2**).

arXiv:2312.13187 [cond-mat.quant-gas]

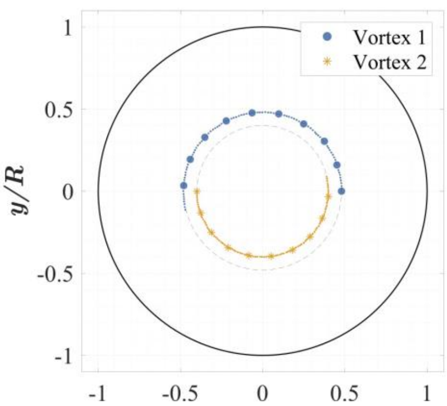

Fig. 1 Gross-Pitaevskii simulation of two mass imbalanced vortices. The dashed lines are the point-like model predictions, for some longer time.

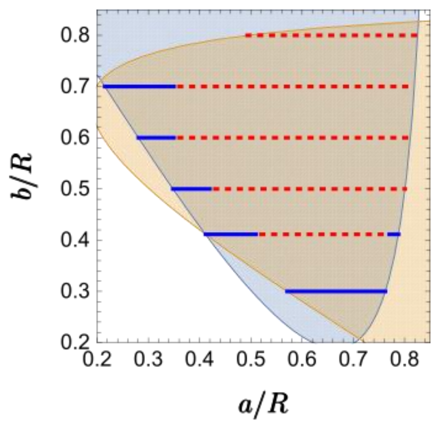

Fig. 2 Regions where at least one of the vortex masses is positive, as a function of *a* and *b*. The plot is symmetric with respect to the exchange of the vortex labels and of *a* and *b*. Ω is fixed. The region $\mathcal{D}$ where the two shaded areas overlap represents all and only the physically meaningful points. Continuous (dotted) segments highlight stable (unstable) CO solutions.

Quantum temperature sensing of ultralow temperature in biwire polar molecules

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In this communication we study quantum temperature sensing for ultralow temperatures in a biwire (tube) polar molecule reservoir with impurity atom qubit serving as a quantum sensor. By means of the quantum signal-to-noise ratio we calculate analytically and numerically the quantum signal-to-noise ratio, the temperature sensing and the non-Markovianity. Our resuts reveal that such quantities are sensitive to the dipolar relative strength and the interwire space.

References

[1] M. A. Cirone, G. De Chiara, G. M. Palma, and A. Recati, New J. Phys. 11, 103055 (2009).
[2] P. Haikka, S. McEndoo, and S. Maniscalco, Phys. Rev. A 87, 012127 (2013).
[3] K. Mohammed Elhadj, A.Boudjem\^aa and U Al-Khawaja, Phys. Scr. 94, 085402 (2019).
[4] Ji-Bing Yuan, Bo Zhang, Ya-Ju Song, Shi-Qing Tang, Xin-Wen Wang, and Le-Man Kuang, Phys. Rev. A 107, 063317 (2023).

Observation of real space pairing in a strongly correlated few-fermion system

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Strong correlations and entanglement are crucial for many phenomena of modern physics such as high temperature superconductivity and the expansion of the early universe. Deciphering these correlations poses a challenging task for theorists and experimentalists. In our cold atom experiment we build complexity from the bottom up, by deterministically preparing a small number of ^{6}Li atoms in the ground state of a 2D harmonic oscillator potential. Owing to our experimental ability to measure both momentum- and real- space density with single particle resolution we directly observe the emergence of many body phenomena such as Cooper pairing [1] or elliptic flow [2].

Currently we are focused on gaining deeper insights on pairing by studying real space correlations in the trapped system. We explore the transition from the two-particle bound state to the many-body Cooper pairs in dependence of both particle number and interaction strength. Additionally, we observe the build-up of a Fermi surface in real space - a special feature of the trapped system where translational symmetry is broken.

Future objectives include studying the thermalization of few fermionic atoms, exploring open shell configurations akin to nuclear physics, and observing interference among identical few-body systems.

References

[1] M. Holten et al. Nature 606 (2022)
[2] S. Brandstetter, P. Lunt et al. arXiv: 2308.09699v1 (2023)

Strong long-range interactions and geometrical frustration in subwavelength Raman lattices

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Non-local interactions are the key building block to allow for a spontaneous breaking of the translational symmetry. The latter represents one of the most fundamental symmetries in physics as it reflects the formation of periodic structures of mass and electric charge. Quantum matter with such a feature falls in the class of spontaneously symmetry broken (SSB) many-body phases with broken translational invariance. Their ubiquity in nature has made the investigation and creation of such states of matter of central importance. In this respect, quantum simulators made of ultracold magnetic atoms with large magnetic dipolar momentum (e.g., erbium) represent a promising and powerful resource. However, current setups only explore frustrated regimes with weak local interactions or regimes where quantum fluctuations are suppressed. To the best of our knowledge, there are no experimental schemes able to simultaneously realize long-range interactions and geometrical frustration.

Here we consider a possible alternative to current setups - a recently realized subwavelength lattice formed by a pair of counter-propagating lasers driving two photon Raman transitions in an ensemble of ultracold atoms. It was shown that one may precisely control the tunneling amplitude, range, and phase by tuning the detunings. One also achieves significantly stronger interactions in the proposed scheme due to its subwavelength nature. Thus, one may realize intriguing phases of matter, such as density waves and chiral superfluids. Our results show several possible scenarios may occur, depending on the lattice depth and detunings.

References

[1] R. P. Anderson et al., Phys. Rev. Research **2**, 013149 (2020).
[2] D. Burba et al., Phys. Rev. A **107**, 023309 (2023).

Coherent transport of Bose-Einstein condensates in asymmetric moving optical lattices

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This study explores the impact of asymmetric moving optical lattices on Bose-Einstein condensates (BECs), with a focus on enhancing coherence and transport efficiency compared to standard symmetric optical lattices [1]. Specifically, we examine the case of ^{87}Rb BEC to illustrate our investigation. Cold atoms confined within a moving optical lattice offer a highly controllable environment for studying transport phenomena [2]. Quantum transport simulations of BECs confined in optical lattices have greatly contributed to our understanding of complex quantum phenomena and their potential applications [3]. However, such simulations often encounter spurious effects, including the emergence of additional peaks at $\pm 2\hbar k_L$ positions in the momentum distribution, which can compromise result accuracy. To address this issue, we propose a novel approach utilizing asymmetric lattice ratchets instead of traditional optical lattices. By employing asymmetric lattice configurations, we aim to mitigate the appearance of additional peaks and enhance the accuracy of quantum transport simulations. Our study contributes to advancing the understanding of BEC dynamics within optical lattices and opens avenues for exploring their applications in diverse quantum systems.

References

[1] R Chamakhi, H Ahlers, M Telmini, C Schubert, E M Rasel and N Gaaloul, NewJ.Phys.17, 123002 (2015)
[2] R Chamakhi, H Ahlers, M Telmini, C Schubert, E M Rasel and N Gaaloul, NewJ.Phys.18, 118002 (2016)
[3] R Chamakhi, M Telmini and N Gaaloul, Editions Universitaires Européennes, EUE (2016)

Entanglement and correlations induced by dynamical quantum phase transitions

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Recently, the concept of dynamical quantum phase transition (DQPT) has received considerable attentions due to the analogy between an equilibrium partition function and the return probability for a many-body wavefunction. During an unitary quantum evolution, the nonanalytical behavior of the return probability defines the occurrence of DQPTs. Albeit the existing studies of DQPTs in various systems, the investigations on the relations between DQPTs and quantum entanglement are still rare. In this work, we take a one-dimensional traverse field Ising model as an example and explore on how quantum entanglement evolves upon DQPTs. The dynamics is triggered by a sudden change of the transverse field strength and we monitor the evolution of quantum entanglement quantified by the corresponding quantum fisher information. Among various quench protocols, we investigate the optimal way to generate quantum entanglement.

A counter-diabatic route to realize dynamical many-body freezing in the periodically driven Lipkin-Meshkov-Glick model

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In recent years, counter-diabatic (CD) driving has emerged as a powerful tool to speed up adiabatic evolution in quantum systems by suppressing non-adiabatic excitations. In this work, we explore the effectiveness of CD protocols in suppressing Floquet heating by analyzing the periodically driven Lipkin-Meshkov-Glick model. Intriguingly, we discover a large parameter regime, where CD driving leads to dynamical many-body freezing and eternal entanglement oscillations for certain initial states. More generally, we find that CD driving leads to Floquet eigenstates with anomalously low entanglement and consequently a lowering of the average eigenstate entanglement. Our results suggest that CD driving protocols may provide a powerful route to realize long-lived Floquet phases of matter.

Quantum Gas Microscopy of a Continuous Fermi Gas at Zero Temperature

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Fermionic systems adhere to Pauli exclusion, one of the most fundamental principles of quantum mechanics that prevents identical fermions from occupying the same quantum state. This leads to an antibunching of particles which manifests itself in density-density correlations and sub-Poissonian number fluctuations. Here we present the direct, in situ observation of antibunching at the single-atom level. Using a newly developed Lithium 6 quantum gas microscope devoted to the study of continuous many-body systems, we probe both the density correlations and number fluctuations in a two-dimensional, noninteracting Fermi Gas. At zero temperature, we observe distinct antibunching behavior in the density correlations as well as a clear suppression of the number fluctuations in the gas. These results represent the first application of a quantum gas microscope to a many-body system in continuous space and offer the perspective to probe strongly interacting Fermi gases in free space at an unprecedented length scale.

Many-body physics with ultracold atoms: From Bethe strings to anyons in one dimension

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Over the past decade, one-dimensional (1D) ultracold gases have proven to be a powerful testbed for studying many-body physics both in and out-of-equilibrium. Here, using ultracold bosonic Cesium (Cs) atoms, we study diverse range of phenomenon arising from the interplay of dimensionality [1], interaction and disorder [2].

In the first experiment, we experimentally realize Bethe-strings, multi-particle bound states in the attractive Lieb-Liniger model and are protected by integrability. In particular, we study the non-equilibrium dynamics of these complex bound states by employing recently developed generalized hydrodynamics (GHD).

Next, in a series of experiments, we study impurity dynamics in 1D. In particular, we realize 1D anyons with arbitrary exchange statistics using our ultracold Cs quantum simulator. We use a 1D gas of spinful hardcore bosons prepared in a finite momentum ground state and exploit the phenomenon of spin-charge separation. In particular, we realize a system of hardcore anyons with a fully tunable statistical phase and observe the asymmetric momentum distribution, hallmark of anyonic correlations. Starting with bosons, we change the statistical parameter to transmute bosons via anyons to fermions.

References

[1] Y Guo, Nature Physics, 1-5 (2024)
[2] Y Guo, arxiv:2312.13880 (2023)

Quantum simulation with Erbium atoms in optical-tweezer arrays

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Neutral atoms in optical tweezers are one of the most promising platforms for quantum simulation and computation as they offer the implementation of arbitrary geometries, dynamical reconfiguration, generation of free-defects arrays and controllable long-range coupling via Rydberg-mediated interactions [1,2]. In this context, lanthanide atoms provide a complex electronic structure, which leads to a rich plethora of optical transition for efficient laser cooling and quantum state preparation [3]. Additionally, the presence of the submerged *f*-shell gives rise to a variety of excitation routes to Rydberg states, which can be exploited for direct optical excitation of large-angular-momentum states yielding the possibility of simulating quantum field theories [4].
We will present our results on the successful loading and detection of single erbium atoms in a linear array of optical tweezers. In our experiment, single atoms detection is accomplished by two complementary techniques: a narrow-linewidth imaging for non-destructive atom detection and a broad-linewidth ultrafast imaging. To achieve single atom occupancies, we characterized the differential light shift for the intercombination line of erbium, and we investigated on the light-assisted collisions (LAC) and heating-induced losses. In addition, in a previous study, we have identified approximately 550 states in the erbium Rydberg series, including a possible state from the *g*-series to which excitation is only possible due to the incompletely filled erbium *f*-shell [5]. These results lay the foundations for realising a quantum simulator based on high angular momentum Rydberg states of single erbium atoms in optical tweezers.

References

[1] A. M. Kaufman, and K.-K. Ni, Nature Physics **17**, 1324 (2021)
[2] A. Browayes, and T. Lahaye, Nature Physics **16**, 132 (2020)
[3] M. Norcia, and F. Ferlaino, Nature Physics **17**, 1349 (2021)
[4] A. Kruckenhauser, R. van Bijnen, T. V. Zache, M. Di Liberto, P. Zoller, Quantum Sci. Technol. 8, 015020 (2023)
[5] A. Trautmann, M. J. Mark, P. Ilzhöfer, H. Edri, A. El Arrach, J. G. Maloberti, C H. Greene, F. Robicheaux and F. Ferlaino, Phys. Rev. Research **3**, 033165 (2021)

Subradiant Excitations in Atomic Arrays with Twisted Light

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Dense ensembles of optically trapped cold atoms exhibit strong dipole-dipole interactions, resulting in collective behaviours such as subradiance. Here, atoms begin to decouple from the quantum vacuum and radiate far slower than individual emitters. However, this same protection from the environment makes them difficult to excite, with typical optical beams exciting only a small fraction of subradiant states. Previous research has analysed symmetry-breaking atomic level shifts to improve excitation efficiency [1]. We extend this work by considering twisted light beams with optical vortices. The inhomogeneous phase of the optical vortex which can change on length scales smaller than the wavelength provides a local driving phase for each atom's dipole moment that improves the ability to target subradiant modes, specifically antiferromagnetic modes. Through a full quantum analysis under a master equation approach and a complementary semi-classical analysis with the coupled dipole model [2], we study the interplay between twisted light driving and subradiant dynamics.

References

[1] G. Facchinietti et al, Phys. Rev. Lett. **117**, 243601 (2016)
[2] M.D. Lee et al, Phys. Rev. A **93**, 063803 (2016)

Angular Bloch Oscillations and their applications

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To advance precise inertial navigation, we present a compact quantum sensor which is based on novel quantum phenomenon of the angular Bloch oscillations [1] and measures solely the angular acceleration of slow external rotation. We investigate the dynamics of ultra-cold atoms confined in a toroidal trap with a ring-lattice along the azimuth angle, realized with the superposition of two copropagating Laguerre-Gaussian beams. In the presence of external rotation of small angular acceleration, or prescribed linear chirp between the two beams, the measured angular momentum of trapped atoms displays a specific periodic behaviour in time, which we name as the angular Bloch oscillations. This discovered quantum phenomenon is shown to be a key element of fruitful applications for (i) an efficient transfer of *quantized* angular momentum from light field to atoms, and (ii) realization of compact quantum sensor to measure exclusively the angular acceleration of external rotation.

References

[1] B. Konrad and M. Efremov, Angular Bloch Oscillations and their applications, arXiv:2402.12826 (2024)

Wannier states in photonic time crystals

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We investigate photonic time crystals in a spatially homogeneous non-magnetic medium. A strong periodic modulation of the permittivity tensor is applied such that we observe distinct gaps in the dispersion relation of the quasienergies in the Floquet description. We investigate the electric and magnetic field intensities and find Wannier states for these fields, which are localized in the time domain. This is achieved numerically by imposing periodic boundary conditions, which corresponds to the consideration of a ring of finite size in time, on which only a discrete set of quasienergies is allowed in each band. We examine numerically the expected relation of orthonormality of the set of Wannier functions localized at different lattice sites, with an aim towards using these as a computational basis for solving Maxwell's equations in periodically modulated media in an effective tight-binding approximation.

Programmable quantum simulator with Strontium Rydberg atoms in optical tweezer arrays

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Electronically highly excited (Rydberg) atoms constitute a system with controllable long-range interactions which allows to study and simulate many intriguing phenomena, ranging from quantum non-linear optics to quantum magnetism and dipole-mediated energy transport [1]. The underlying dynamics depend on the structure, dimensionality and interaction type of the physical system. Disentangling and controlling their contributions is an open problem, whose solution may empower new technology, including realizing general purpose quantum computers.

Such challenge is addressable by studying model systems in highly controllable experiments that capture their key features. Ultra-cold interacting Rydberg Strontium atoms trapped in reconfigurable arrays of optical tweezers represent such tailored quantum simulator. Strontium provides several sets of atomic states, including metastable ones[2], that are conveniently mappable into magnetic spins or quantum bits. Single- or two-photon excitation pathways to nS, nP and nD Rydberg states allow to engineer and fine-tune dipole-mediated interactions that can picture different spin or energy transport scenarios and also realize quantum gates [3]. I will present our progress with the construction of the setup and outline our planned capabilities, including the creation of up to three-dimensional large structures of optical tweezers with single site addressability and manipulation ability.

References

[1] Browaeys, A., Lahaye, T., Many-body physics with individually controlled Rydberg atoms, Nature Physics 16, 132-142 (2020)

[2] Sorrentino, F., Ferrari, G., Poli, N., Drullinger, R., Tino, G. M., Laser Cooling And Trapping Of Atomic Strontium For Ultracold Atoms Physics, HighPrecision Spectroscopy And Quantum Sensors, Modern Physics Letters B 20, 21 (2006)

[3] Saffman, M., Walker, T. G., Mølmer, K., Quantum information with Rydberg atoms, Rev. Mod. Phys. 82, 3 (2010)

Indication of critical scaling in time during the relaxation of an open quantum system

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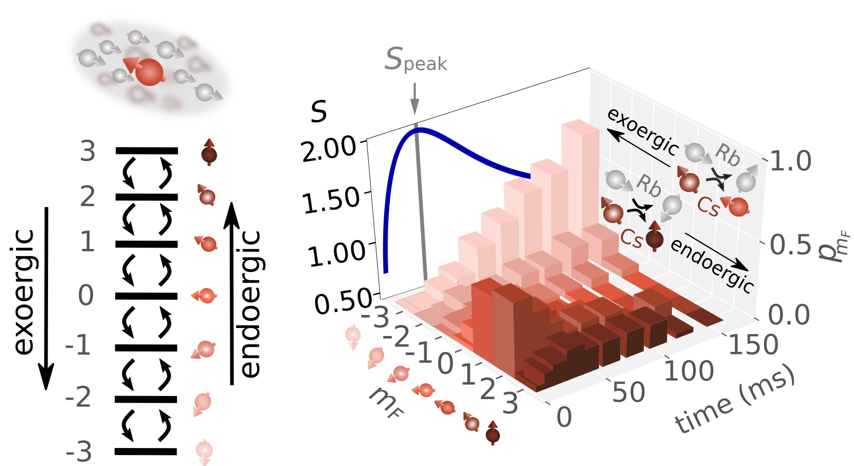
Near continuous phase transitions, universal power-law scaling, characterized by critical exponents, emerges. This behavior reflects the singular responses of physical systems to continuous control parameters like temperature or external fields. Universal scaling extends to non-equilibrium dynamics in iso- lated quantum systems after a quench, where time takes the role of the control parameter. Our research unveils critical scaling in time also during the relaxation dynamics of an open quantum system. Here we experimentally realize such a system by the spin of individual Cesium atoms dissipatively coupled through spin-exchange processes to a bath of ultracold Rubidium atoms. Through a finite-size scaling analysis of the entropy dynamics via numerical simulations, we identify a critical point in time in the thermodynamic limit. This critical point is accompanied by the divergence of a characteristic length, which is described by critical exponents that turn out to be unaffected by system specifics.



Faraday waves driven by Rabi oscillations on a bubble Bose-Einstein condensed mixture

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(Dated: May 29, 2024)

We study the dynamic stability of Bose-Einstein condensed binary mixtures trapped on the surface of an ideal two-dimensional spherical bubble, with the two species coupled by Rabi oscillations, which modulate the interactions and can lead to parametric resonances. In this spherical geometry, it is verified that discrete unstable angular modes drive both the phase separation and spatial pattern, with Faraday waves emerging and coexisting with an immiscible phase. The stability of homogeneous miscible species is investigated by performing the Bogoliubov-de Gennes and Floquet methods. A straightforward way to check the predictions is also provided by full a dynamics analysis, performed numerically for the corresponding time-dependent Gross-Pitaevskii coupled formalism.

[1] L. Brito, L. Tomio, A. Gammal, Phys. Rev. A **108**, 0533015 (2023).

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Rotation-Induced Supersolidity of a Dipolar Bose-Einstein Condensate Confined in a Bubble Trap

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Motivated by the recent realization of space-borne Bose-Einstein Condensate (BEC) under microgravity conditions, we extend the understanding of ultracold dipolar bosonic gases by exploring their behaviour in a novel trapping configuration known as the “bubble trap” topology. Utilizing the three-dimensional numerical simulations within the extended Gross-Pitaevskii framework, we unveil diverse ground state phases in such a static curved topology. Subsequently, we investigate the influence of rotation on a dipolar BEC confined to the surface of a spherical bubble. Our findings reveal that the rotation of a bubble trap with certain rotation frequencies can modify the effective local dipole-dipole interaction strength, leading to the induction of supersolidity and the formation of quantum droplets. In addition, we demonstrate that a bubble trap can sustain high circulation and the flow also persists for a longer time. Significantly, adjusting the rf detuning parameter allows the condensate to achieve hypersonic velocity. Finally, we explore the impact of drastic change in the topological nature of the trap on the rotating dipolar BEC, transitioning from a filled shell trap to a bubble trap and vice versa.

Engineering Floquet-Feshbach Resonances

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Feshbach resonances play a crucial role in the study of ultracold atoms. These scattering resonances allow for the precise tuning of interaction strength, spanning from attractive to repulsive regimes. Since their initial experimental observation in a Bose-Einstein condensate in 1998 [1], they have become widely adopted within the ultracold atom community. The existence of experimentally exploitable Feshbach resonances depends on the scattering potential between two atoms, with their magnetic field position and width determined by fundamental physical properties.

In this contribution, we discuss a novel method to induce and engineer new resonances by applying a strong oscillating magnetic field collinear to the quantization axis. The method was first theoretically investigated by Smith [2], who showed that resonance position and width are governed by the driving frequency and amplitude. Lithium-6 exhibits a broad s-wave resonance at 832 G due to a weakly bound halo state, making it an ideal candidate for experimental realization of these novel resonances. By employing Floquet theory, we transform the time-dependent problem into a time-independent equivalent, enabling theoretical investigations using coupled-channel calculations. We will present the theoretical findings from these calculations and discuss the current status of experimental realization.

References

[1] S. Inouye, et. al. Nature **392**, (1998)
[2] D. H. Smith, Physical Review Letters **115**, (2015)

Non-perturbative corrections to the weakly interacting two component Fermi gas

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A simplified mean-field description of fermionic systems relies on the Hartree-Fock-Bogoliubov (HFB) approach, where the two-particle interaction is decomposed into three distinct channels. A major issue with this method is that the separation between the channels is somewhat arbitrary. Depending on the physical situation to be described, different channels turn out to be important.
In this poster, we present a self-consistently generalized mean-field theory, which is based on introducing a separate weighting factor for each channel. This ansatz removes the arbitrariness of the channel separation by providing an extremization principle for their optimal partitioning.
The power of our technique is illustrated by considering the example of two unpolarized fermionic species with contact interaction. In this case the Fock contribution vanishes and we obtain a coupling between the Hartree and the Bogoliubov channel. This results non only in first beyond mean-field corrections[1,2] already at the mean-field but also decreases the critical temperature in qualitative agreement to particle-hole fluctuations [3]. Due to the non-perturbative nature of the channel coupling we also obtain results which are not captured by any fluctuation theory in one channel alone. This requires the introduction of an effective interaction range as a new length scale and should become relevant for large enough densities. With this our formalism builds a natural theoretical bridge between fermionic superfluidity in ultracold atomic gases and superconductivity in condensed matter physics as well as the realm of nuclei and neutron matter.

References

[1] C. A. R. Sá de Melo, M. Randeria, J. R. Engelbrecht, Phys. Rev. Lett. **71**, 3202 (1993)
[2] J. R. Engelbrecht, M. Randeria and C. A. R. Sá de Melo, Phys. Rev. B **55**, 15153 (1997)
[3] L. Gor'Kov and T. Melik-Barkhudarov, Sov. Phys. JETP **13**, 1018 (1961)

Energy Damping of a Jones-Roberts Soliton: Analytical and Numerical Results

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Non-linear, form preserving waves known as Jones-Roberts solitons are a class of universal phenomena described by the two-dimensional Gross-Pitaevskii equation. Encompassing vortex dipoles as well as rarefaction pulses, they feature prominently in the dynamics of Bose-Einstein condensates (BECs). As they prove to be stable against perturbations, finite temperature effects can be expected to have a major influence on their damping. We investigate the thermally induced decay of Jones-Roberts solitons in the framework of the stochastic projected Gross-Pitaevskii equation. Our findings suggest that the dominant damping mechanism is energy damping, stemming from the scattering between atoms in the thermal cloud and the condensate region without the exchange of particles between them. While in the vortex dipole regime the characterising property of a Jones-Roberts soliton is the distance between the vortices, we identify the interaction energy as the relevant quantity in the rarefaction pulse regime. We present analytical and numerical results demonstrating the decay behaviour of these parameters for different kinds of damping expected in thermal BECs. A comparison of these decay processes than reveals the dominance of energy damping for experimentally relevant parameters.

Measuring the dipolar interaction shift of the BEC critical temperature

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Interactions in many-body bosonic systems lead to a shift of the critical temperature for Bose-Einstein condensation compared to the ideal gas result. The effect in gases with purely contact interactions has been thoroughly studied, both theoretically and experimentally. This work presents our measurements of the 'mean-field' critical temperature shift due to magnetic dipole-dipole interactions in a harmonically trapped, ultracold erbium gas. Analysing the transition temperature dependence on the orientation of the dipoles in a highly prolate trap, we isolate the contribution of the anisotropic dipolar interactions and demonstrate the agreement with predictions [1]. Additionally, we investigate the role of dipolar interactions to the non-saturation of the thermal gas past the transition [2], and outline a Thomas-Fermi approximation based model to explain the observation. These findings may enhance imaging calibration accuracy in cold atom experiments and could enable studies of beyond-mean field effects in the BEC transition in dipolar gases.

References

[1] K. Glaum et al, Phys. Rev. Lett. **98**, 080407 (2007)
[2] N. Tammuz et al, Phys. Rev. Lett. **106**, 230401 (2011)

Synthetic Gauge Fields in the Tripod and Double Tripod Systems

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We experimentally study synthetic gauge fields using the tripod and double tripod systems in a gas of neutral ultracold strontium atoms. In the tripod system, we resonantly couple three nearly degenerate Zeeman $^1S_0$ ground states of strontium-87 atoms to a Zeeman substate of the $^3P_1$ excited state. In the dressed state picture, this coupling gives rise to two bright eigenstates and two degenerated dark eigenstates. Within the adiabatic limit, the evolution of an atom initially prepared in one of the dark states can be effectively described as being in the presence of an SU(2) synthetic gauge field, with a non-abelian nature [1]. Interestingly, even when the non-abelian gauge field is uniform, the dynamics of the atoms can be non-ballistic. This is due to a spin-orbit coupling arising from the gauge field, which leads to spin-hall characteristics and a zitterbewegung-like effect in the dynamics [2]. We then extend our studies to create synthetic SU(3) gauge field by including additionally two ground states and one excited state, leading to a double tripod system [3] with a degenerate dark state manifold of dimension three. Our preliminary results show that the system experiences SU(3) color-orbit coupling with a rich behavior.

References

[1] F. Wilczek and A. Zee, "Appearance of Gauge Structure in Simple Dynamical Systems", Phys. Rev. Lett. 52, 2111 (1984)

[2] M. Hasan, C. S. Madasu, K. D. Rathod, C. C. Kwong, Ch. Miniatura, F. Chevy and D. Wilkowski, "Wave Packet Dynamics in Synthetic Non-Abelian Gauge Fields", Phys. Rev. Lett. 129, 130402 (2022)

[3] Y.-X. Hu, Ch. Miniatura, D. Wilkowski and B. Grémaud, "U(3) artificial gauge fields for cold atoms", Phys. Rev. A 90, 023601 (2014)

Emergence of orbital physics with ultracold bosons in the BBH model

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Chirality is a central concept to describe a large class of phases of matter, including certain topological phases, and quantum simulators provide a unique opportunity to explore the corresponding properties. A particularly interesting case of study is the Benalcazar-Bernevig-Hughes (BBH) model for two-dimensional lattices with pi-flux, which is known to belong to the higher-order insulators family. It has been recently shown that chiral properties and phases resembling those of higher bands emerge in the low-energy physics of this model with bosons at half filling [1], especially in the weakly interacting regime and on the strongly-interacting 1D ladder case. Here, we focus on the two-dimensional strongly-interacting case to clarify the quantum phases of the model, the corresponding phase diagram via relevant observables and the low-energy spectrum near criticality. We employ variational techniques based on the Gutzwiller ansatz, a local product state ansatz, extended to include short-range correlations, to characterize the emergence of local angular momentum states via symmetry breaking.

References

[1] Di Liberto, M. and Goldman, N. 'Chiral orbital order of interacting bosons without higher bands', Physical Review Research, 2023, 5.2: 023064

Study of vortices interaction and solitons in a quantum fluid of light

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Quantum fluids Physics is the study of hydrodynamic systems which demonstrate a quantum behavior. We study here a fluid of photons that can acquire an effective mass due to the interaction with a hot vapor of Rubidium atoms. Fluid behavior then arises from an analogy between the nonlinear Schrödinger equation and Gross-Pitaevskii equation. Dimensionless temporal and spatial scales derived respectively from the nonlinear interaction strength and healing length are then used to characterize the evolution of the fluid.

The group has shown experimental demonstrations of superfluidity and other quantum hydrodynamical effects such as quantized vortices and solitons.[1,2,3] More specifically, I will present recent results on the generation of Jones-Roberts solitons from the merging of 2 vortices of opposite sign. Vortices are imprinted optically in the fluid and the merge thanks to interaction. The resulting soliton is seen to propagate without deformation in the fluid.

References

[1] M. Baker-Rasooli, Phys. Rev. A **108**, 063512 (2023)
[2] M. Abuzarli, EPL **134**, 24001 (2021)
[3] T. Bienaimé, Phys. Rev. Lett. **129**, 100602 (2022)

Vortex dynamics in Fermi superfluids across the BEC-BCS crossover

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On of the most interesting features of superfluidity is the appearance of quantized vortices. This is well-studied for Helium and for atomic BECs, but not so much for Fermi superfluids. We study vortices in Fermi superfluids throughout the BEC-BCS crossover and at different temperatures using an effective field theory. This effective field theory reduces to the Gross-Pitaevskii model in the BEC limit and at zero temperature but contains extra terms in the crossover and in the BCS regime or at nonzero temperatures. From a phenomenological point of view, vortices are often studied in a point-vortex model containing mutual friction parameters. We aim to calculate these coefficients by simulating the real-time dynamics of a vortex-antivortex pair within this effective field theory framework, and by fitting the trajectories of the vortices to the predictions of the point-vortex model.

Collective oscillation modes of dipolar quantum droplets

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Since the first experimental realization of quantum droplets in dipolar Bose systems [1], it was shown [2] that they are stabilized against the collapse due to quantum fluctuations that correspond to the shift of the chemical potential [3]. We examine the behavior of collective oscillation modes of self-bound dipolar quantum droplets using a variational and numerical approach. We focus on cylindrically symmetric states and variationally derive frequencies and eigenvectors of low-lying collective modes, i.e., the breathing and the quadrupole mode. The obtained results are compared to full 3D numerical simulations based on the extended Gross-Pitaevskii equation, which includes both the quantum fluctuation and condensate depletion terms.

References

[1] H. Kadau et al., Nature 530, 194 (2016).
[2] I. Ferrier-Barbut et al., Phys. Rev. Lett. **116**, 215301 (2016).
[3] A. R. P. Lima and A. Pelster, Phys. Rev. A **84**, 041604(R) (2011); ibid. Phys. Rev. A **86**, 063609 (2012).

Projection optimization method for open-dissipative quantum fluids and its application to a single vortex in a photon Bose-Einstein condensate

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Open dissipative systems of quantum fluids have been well studied numerically. In view of a complementary analytical description we extend here the variational optimization method for Bose-Einstein condensates of closed systems to open-dissipative condensates. The resulting projection optimization method is applied to a complex Gross-Pitaevski equation, which models phenomenologically a photon Bose-Einstein condensate. Together with known methods from hydrodynamics we obtain an approximate vortex solution, which depends on the respective open system parameters and has the same properties as obtained numerically in the literature.

References

[1] J. Krauß, M.A.G. dos Santos Filho, F.E.A. dos Santos, and A. Pelster, arXiv:2311.10027 (2023).

Quantum simulations with an atomic tweezer array strongly coupled to a Fiber Fabry-Perot Cavity

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The study of N two-level systems involved in long-range interactions holds interest for quantum simulation and information. An ideal candidate would be N individually controlled neutral atoms interacting via the resonant pho- tons of a Fabry-Perot cavity, in a Cavity Quantum Electrodynamics (CQED) scenario.
In our group, high-finesse Fibre Fabry-Perot Cavities (FFPCs) are made with laser-machined mirrors, allowing small mode cross-section and thus strong light-matter coupling for a single emitter. The N atoms are separately trapped using an array of far-off-resonance, tightly-focused laser beams (optical tweezers).
We are currently working on the characterization of quantum states in the low-excitation regime, which involve a hybrid light-matter mode: the polariton. This quantum state is comprised of a superposition between a single atomic excitation shared by all emitters and a single photon in the resonant field mode. It has been shown that polaritons can emerge even when the qubit frequency distribution is inhomogeneous. Experimental investigation of the transition from disordered to polaritonic regime remains mostly unexplored.
In this presentation, I will discuss a technique that allows controllable detuning of the atomic frequency distribution through the control of the polarization of the tweezers, which exert a site and position-dependent light shift on the atomic levels. The high degree of control over the frequency distribution makes this experiment a model for molecular polaritons chemistry, or quantum simulation of organic semiconductors.

Temporal bistability in the dissipative Dicke-Bose-Hubbard system

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A driven-dissipative, atomic Bose-Einstein condensate in 2D Hubbard lattice, coupled to an optical cavity mode exhibits several atomic phases including superfluid and supersolid corresponding to normal and superradiant photonic phases, respectively. We investigate the dynamical behaviour of the system, where we include dissipation by means of Lindblad master equation formalism. Due to the interplay between strong, repulsive Hubbard interaction and atom-cavity coupling, we find an extended coexistence region around the Dicke normal-to-superradiant transition. We study the resulting switching dynamics between the coexisting phases, which eventually become damped by dissipation.

References

[1] Tianyi Wu, Sayak Ray and Johann Kroha, Ann. Phys., 2300505 (2024).

Inelastic Confinement Induced Resonances: Tool or Limitation for Quantum Sensing and Simulation?

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Inelastic confinement-induced resonances (ICIR) are a universal phenomenon occurring if the relative motion couples to the center-of-mass motion due to an external confining potential, as it is the case, e.g., for ultracold atoms or molecules in an optical tweezer or lattice. At an ICIR not only the interaction strength can be tuned, as is the case also for so-called elastic confinement-induced resonances (ECIRs), but also dimer (molecule) formation is possible and was observed. Furthermore, in the case of dipolar interaction like, e.g., for heteroatomic molecules or atoms with a magnetic moment the position of the ICIRs can be tuned with external fields. Very recently, ICIRs were experimentally observed for three-dimensional trap geometries [1], i.e. in contrast to ECIRs that can only occur for (quasi) one- or two-dimensional geometries, and even for atoms at neighbor sites of an optical lattice [2], thus being tunneling mediated. Evidently, the knowledge on the occurrence of ICIRs is vital, if ultracold quantum gases are used for applications as quantum sensors, quantum simulators, or quantum-computers, since otherwise results may be misinterpreted. On the other hand, they may offer new possibilities for these quantum-technology applications.

[1] D. Capecchi, C. Cantillano, M. J. Mark, F. Meinert, A. Schindewolf, M. Landini, A. Saenz, F. Revuelta, H.-C. Nägerl, Phys. Rev. Lett. 131, 213002 (2023).

[2] Y.K. Lee. H. Lin. W. Ketterle, Phys. Rev. Lett. 131, 213001 (2023)

Estimating the magnitude of the homogeneous perturbations by measuring the number of BEC molecules in ultracold chemical reactions

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Sensors using chemical chain reactions have been widely used in biological and chemical analysis. Contrary to these classical chemical reactions, at extremely low temperatures (~ 100 nK), ultracold chemical reactions may occur in Bose-Einstein condensates (BEC) where the coherent oscillatory dynamics may occur even for the simplest reactions like $A + A \leftrightarrow A_2$.

In an atom-molecule BEC under ultracold chemical reactions $A + A \leftrightarrow A_2$, by calculating the quantum Fisher information (QFI) and the lower bound of the classical Fisher information (CFI), we show that one can estimate the magnitude of the homogeneous external perturbations by measuring the number of BEC molecules [1]. Counting the number of BEC molecules under ultracold chemical reactions is simpler compared to previous proposals that rely on counting the number of phonons in BEC to detect external perturbations. This is because spectroscopic techniques can be used to count the number of BEC molecules, while there are several challenges in counting the number of phonons in BEC [2, 3].

Also, in our system, the lower bound of the CFI can reach up to around 60% of the QFI, meaning that the sensor relying on counting the number of BEC molecules is close to the optimal sensor for detecting the homogeneous external perturbations.

References

[1] Seong-Ho Shinn, Uwe R. Fischer, and Daniel Braun, arXiv:2208.06380 [cond-mat.quant-gas]
[2] Ralf Schützhold, Phys. Rev. D **98**, 105019 (2018)
[3] Dennis Rätzel and Ralf Schützhold, Phys. Rev. A **103**, 063321 (2021)

Towards Discrete Time Crystals with Bouncing Bose-Einstein Condensates

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Our project aims to experimentally demonstrate that weakly interacting Bose condensed atoms bouncing on a periodically driven atomic mirror can spontaneously break time-translational symmetry to form a discrete time crystal [1]. The resonantly tuned bouncing ensemble can evolve along long-lived stable orbits with a period multiple times larger than the driving period thus exhibiting subharmonic oscillations and creating a large number of atomic lattice sites in the time domain. Our approach [2] is based on the use of potassium-39 atoms which have several convenient Feshbach resonances to precisely tune attractive atomic interactions in the vicinity of the zero crossing. We will report on our progress towards the preparation of a Bose condensed ensemble of potassium-39 atoms about 200 μm above the driven atomic mirror made from a 532 nm fibre laser. In a successful demonstration the creation of discrete time crystals with large atom numbers occupying multiple temporal lattice sites will offer a unique way to perform condensed matter physics experiments in the time domain.

References

[1] K. Giergiel, A. Kosior, P. Hannaford and K. Sacha, Physical Review A **98**, 013613 (2018).

[2] K. Giergiel, T. Tran, A. Zaheer, A. Singh, A. Sidorov, K. Sacha, and P. Hannaford, New Journal of Physics **22**, 085004 (2020).

Correlations of strongly interacting ultra-cold p-wave fermions in one-dimensional trap

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We consider many-body ground state of polarized fermions interacting via p-wave forces and confined in one-dimensional trap of some shape. We show the mathematically rigorous prove that in the limit of infinite attractions mutual correlations between any two subsystems are absolutely insensitive to the shape of external trapping. This unique property of a system of polarized fermions is a non-trivial consequence of quantum statistics, subtlety of p-wave interactions and dimensionality.

References

[1] P. Kościk and T. Sowiński, Phys. Rev. Lett. **130**, 253401 (2023)

Bogoliubov theory of 1D anyons in a lattice

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In a one-dimensional lattice anyons can be defined via generalized commutation relations containing a statistical parameter, which interpolates between the boson limit and the pseudo-fermion limit. The corresponding anyon-Hubbard model is mapped to a Bose-Hubbard model via a fractional Jordan-Wigner transformation, yielding a complex hopping term with a density-dependent Peierls phase. Here we work out a corresponding Bogoliubov theory. To this end we start with the underlying mean-field theory, where we allow for the condensate a finite momentum and determine it from extremizing the mean-field energy. With this we calculate various physical properties and discuss their dependence on the statistical parameter and the lattice size. Among them are both the condensate and the superfluid
density as well as the equation of state and the compressibility. Based on the mean-field theory we then analyse the resulting dispersion of the Bogoliubov quasi-particles,
which turns out to be in accordance with the Goldstone theorem. In particular, this leads to two different sound velocities for wave propagations to the left and the right, which originates from parity breaking.

References

[1] Martin Bonkhoff, Kevin Jägering, Sebastian Eggert, Axel Pelster, Michael Thorwart and Thore Posske, *Phys. Rev. Lett*. **126**, 163201 (2021).
[2] Keilmann, T., Lanzmich, S., McCulloch, I. et al. *Nat Commun* 2, 361 (2011)

Localization phenomenon in Rydberg-gadget networks

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We study the quantum dynamics of the encoding scheme proposed in [Nguyen et al., PRX Quantum 4, 010316 (2023)], which is designed to encode optimization problems on graphs with arbitrary connectivity into Rydberg atom arrays. Here, a graph vertex is represented by a wire of atoms, and the (crossing) crossing-with-edge gadget is placed at the intersection of two wires to (de)couple the wire degrees of freedom, reproducing the graph connectivity. We consider the exemplified geometry of two wires intersecting via a single gadget and look at minimum gap scaling with system size along annealing protocols. We find that both polynomial and exponential scaling are possible and, by means of perturbation theory, we relate the exponential closure of the minimum gap to an unfavorable localization of the wavefunction. We then eventually propose possible strategies to circumvent it, leading to an exponential improvement of the annealing performances.

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Exploring Supersolidity of Dipolar Quantum Gases: Vortex Formation and Neutron Star Analogues

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Due to anisotropic long-range interactions, dipolar quantum gases of Erbium and Dysprosium form an exotic phase of matter called a supersolid, characterized by both density modulation and phase coherence. While density modulation can be directly observed and phase coherence can be probed by self-interference, the superfluid nature of the system in terms of irrotational flow has yet to be shown unambiguously. Quantized vortices, a defining feature of superfluidity, is an unequivocal probe of irrotational flow which can be used to prove the superfluid nature of the supersolid phase. Here we study, both experimentally and theoretically, the creation of vortices in both the unmodulated BEC phase and the modulated supersolid phase of Dy-164. Additionally, we will report on theoretical work linking supersolid vortices to the observed sporadic increase in the rotation speed of pulsars and plans to use ultracold dipolar experiments to simulate the internal dynamics of neutron stars. Finally, we will discuss our recent advances towards a dual-species dipolar quantum gas microscope for the creation of interaction-induced topological insulators.

Non-equilibrium dynamics of strongly interacting Bose-Fermi mixtures

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We develop a conserving dynamical theory of a degenerate Bose-Fermi mixture near an interspecies Feshbach resonance. In contrast to the typical Hartree-Fock-Bogoliubov approximation, our beyond Gaussian theory correctly embeds the microscopic two-body physics in the gas, which is enhanced by the competing influences of the Fermi sea and the Bose-Einstein condensate. We benchmark our theory by studying atom-pair coherence near the Feshbach resonance, where our results show excellent agreement with analytical predictions. Next, we apply our theory to a deep quench of the gas to the unitary regime, characterizing the resulting depletion of the condensate, the deformation of the Fermi surface, and the production of molecules. We furthermore discuss how our theory can be extended to include boson-boson interactions mediated by the fermionic cloud, which were recently observed in experiments.

Cavity-based non-destructive detection in ultracold gases

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Cavity quantum electrodynamics studies the interaction of atoms with the electromagnetic mode of an optical cavity. Placing an atom within a cavity modifies its emission properties either by changing the spontaneous emission rates (weak coupling regime) or by coherent exchange of energy between atom and cavity mode (strong coupling regime). When there are multiple atoms (N_C) inside the cavity mode volume, collective effects emerge. As a result, the atom-cavity system shows vacuum Rabi splitting (VRS), which directly depends on the $\sqrt{N_C}$ (collective strong coupling regime).

This makes cavity a frequency-sensitive detection tool for measuring state-dependent interactions. To demonstrate rapid, continuous cavity-based measurement, we experimentally measure time evolution in a multilevel system and show the potential of cavity-based measurements for state detection, even when there are many participating energy levels. To illustrate the range of applications of the cavity-based detection scheme, we also use the cavity to detect photoassociation in a dark MOT where a direct fluorescence measurement is not possible and use this to determine PA rates in the system [1].

References

[1] V.I. Gokul, A. Bahuleyan, S.P. Dinesh, V.R. Thakar, S.A. Rangwala. “Cavity based non-destructive detection of photoassociation in a dark MOT”. arXiv preprint arXiv:2402.15114

Engineering Hamiltonians in the lab

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In the summer of 2022, the Quantum group of Ghent University experimentally realized the first Belgian Bose-Einstein condensate. This set-up opens the path to engineer and investigate interesting many-body Hamiltonians.
One way to encode Hamiltonians into a BEC system is by applying a periodically driven external potential, an approach broadly known as Floquet engineering [1]. The periodicity of the Hamiltonian enables one to describe the stroboscopic evolution of the system with an effective Hamiltonian. It is then the goal to tailor the driving protocol to implement interesting effective Hamiltonians.
A particular application is the creation of *synthetic dimensions*. The basic idea is to introduce a coupling between internal degrees of the system and re-interpret their behavior as dynamics along a (discrete) synthetic dimension, allowing us to use a continuous BEC to simulate synthetic lattice models and their dynamics. This approach was carried out in [2], [3] for a one-dimensional BEC using standard harmonic oscillator eigenstates as synthetic lattice sites, but leaving out interactions. We are interested in the effect interactions have on the validity of this approach. For example, we can look at the deviation of the dynamics generated by the effective Hamiltonian and those generated by the full, time-dependent Hamiltonian, essentially captured by the so-called *kick operator*. Another important feature is the occurrence of *heating*. When driving our system, the system gets heated and the condensate fraction diminishes. Methods are available to extract the heating rates in function of the parameters of the system drive. These rates are of great interest when designing, in our case 3 dimensional, BEC experiments. Going further, one can then start to think about modified driving protocols to counteract the heating effects and extend the range of validity of the effective description of the system.

References

[1] N. Goldman, Phys. Rev. X **5**, 029902 (2014)
[2] H. Price, Phys. Rev. A **95**, 023607 (2017)
[3] C. Oliver, Phys. Rev. Research **5**, 033001 (2023)

Single-Atom-Resolved Fluctuation Thermometry of quasi-2D Fermi Gases in Continuous Space

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We report on a thermometry technique for non-interacting quasi-2D Fermi gases in continuous space, based on the detection of atom number fluctuations at the single-atom level through quantum gas microscopy. In Fermionic systems, the Pauli exclusion principle leads to sub-poissonian atom number fluctuations which can be connected to the temperature. In small subsystems, however, quantum fluctuations play an important role, leading to a significant deviation from the behaviour predicted by the fluctuation-dissipation theorem in the thermodynamic limit. By accounting for those finite-size effects, we are able to perform accurate fluctuation thermometry over a large dynamical range, from nearly zero temperature to several times the Fermi temperature. Our method could be extended to extract the temperature of single-atom-resolved continuous systems across the BEC-BCS crossover.

Direct Cooling of Dipolar Molecules Towards Bose-Einstein Condensation

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Bose-Einstein condensates (BECs) have been and continue to be extensively studied in atoms, with molecules being a logical next step. Molecules can have large, tunable electric dipole moments so a molecular BEC forms a strongly dipolar quantum fluid and can be used to study many-body physics and for quantum simulations. However, the production of such molecular BECs, either through association of ultracold atoms or direct cooling of the molecules, is very challenging.

In our experiment we produce, cool down, and trap CaF molecules in several steps. The molecules are generated in a cryogenic buffer gas source such that they form a cold molecular beam, then decelerated to rest using frequency-chirped slowing, are finally trapped in a magneto-optical trap (MOT). To reach the lower temperatures and higher densities necessary for the phase transition to a BEC, the molecules need to be cooled further in an optical molasses and compressed using either magnetic compression or the blue-detuned MOT method [1,2]. Afterwards, the molecules will be loaded into a crossed-dipole trap for evaporative cooling until they form a BEC. Two-body losses can be controlled and suppressed by applying an electric field, which will also improve the elastic scattering rate.

References

[1] L. Caldwell, J. A. Devlin, H. J. Williams, N. J. Fitch, E. A. Hinds, B. E. Sauer, and M. R. Tarbutt, “Deep laser cooling and efficient magnetic compression of molecules”, Phys. Rev. Lett. 2019;123:033202

[2] K. N. Jarvis, J. A. Devlin, T. E. Wall, B. E. Sauer, and M. R. Tarbutt, “Blue-detuned magneto-optical trap”, Phys. Rev. Lett. 2018;120:083201

Simulating a periodic driving with a sudden quench in an ultra cold quantum gas

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Based on our previous works [1,2], we construct a model of quantum many-body system with periodic driving of the inter-particle interaction, and show that its evolution can be mimicked by a sudden quench of the trapping frequency. The results present the interplay between two different aspects of quantum dynamics, which are the quench and the Floquet problems, and can allow us to simulate one from another.

References

1. E. Wamba, A. Pelster, and J. Anglin, Phys. Rev. A **94**, 043628 (2016)
2. E. Wamba and A. Pelster, Phys. Rev. A **102**, 043320 (2020)

Floquet Schrieffer-Wolff transform based on Sylvester equations

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We present a Floquet Schrieffer-Wolff transform (FSWT) to obtain effective Floquet Hamiltonians and micro-motion operators of periodically driven many-body systems for any non-resonant driving frequency. The FSWT perturbatively eliminates the oscillatory components in the driven Hamiltonian by solving operator-valued Sylvester equations. We show how to solve these Sylvester equations without knowledge for the eigenstates of the undriven many-body system, using the driven Hubbard model as an example. In the limit of high driving frequencies, these solutions reduce to the well-known high-frequency limit of the Floquet-Magnus expansion. We anticipate that this method will be useful for the description of multi-orbital and long-range interacting systems, which are driven either classically or quantum-mechanically in-gap.

References

[1] X. Wang, F. P. Mendez Cordoba, A. Eckardt, D. Jaksch, and F. Schlawin, Floquet Schrieffer-Wolff transform based on Sylvester equations (in preparation).

[2] X. Wang, D. Jaksch, and F. Schlawin Phys. Rev. B **109**, 115137 (2024).

[3] X. Wang, E. Ronca, and M. A. Sentef, Phys. Rev. B **99**, 235156 (2019).

Solitons on the surface of a sphere

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The recent realization of ultracold quantum gases in a shell geometry [1] paves the way towards a Bose-Einstein condensate (BEC) that is trapped tightly onto the surface of a sphere. We investigate the existence and stability of solitons that appear in this system using the two-dimensional (2D) Gross-Pitaevskii equations (GPE). Comparing our results to the 2D plane, we find that the scale invariance of the GPE is broken due to the curvature and compactness of the shell geometry. Consequently, the familiar Townes solitons [2] appear only when the BEC is strongly localized in a small region of the sphere surface.

References

[1] R. A. Carollo *et al*., Nature (London) **606**, 281 (2022).
[2] B. Bakkali-Hassani *et al*., Phys. Rev. Lett **127**, 023603 (2021).

Unravelling Interaction and Temperature Contributions in Unpolarized Trapped Fermionic Atoms in the BCS Regime

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In the BCS limit density profiles for unpolarized trapped fermionic clouds of atoms are largely featureless. Therefore, it is a delicate task to analyze them in order to quantify their respective interaction and temperature contributions. Temperature measurements have so far been mostly considered in an indirect way, where one sweeps isentropically from the BCS to the BEC limit. Instead we suggest here a direct thermometry, which relies on measuring the line density and comparing the obtained data with a Hartree-Bogoliubov mean-field theory combined with a local density approximation. In case of an attractive interaction between two-components of ^{6}Li atoms trapped in a tri-axial harmonic confinement we show that minimizing the error within such an experiment-theory collaboration turns out to be a reasonable criterion for analyzing in detail measured densities and, thus, for ultimately determining the sample temperatures. The findings are discussed in view of various possible sources of errors.

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Generating entangled helical spin currents in a spinor Bose-Einstein condensate

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We propose the method of generating perfectly helical spin currents by quantum-mechanically entangled two counter-propagating spin currents. To be concrete, we prepare a spin-1 condensate which is initially prepared in the $m = 0$ magnetic sublevel in a one-dimensional torus. We assume that atoms interact via an s-wave scattering channel which parametrically generates an entangled pair of $m = 1$ and -1 atoms from two $m = 0$ atoms [1]. The pair of $m = 1$ and -1 atoms acquire oppositely directed momenta via the Bragg diffraction [2], while they maintain the quantum-mechanical spin correlations. Consequently, a nonzero spin current flows in the torus with no net mass current. In particular, the quantum fluctuation in the mass current is exactly zero.

References

[1] X. Luo, Science **355**, 620 (2017)

[2] M. Kozuma et al., Phys. Rev. Lett. **82**, 871 (1999)

A Rapid Fermionic Quantum Simulator for Random Unitary Observables

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Quantum simulation with ultracold atoms in optical lattices has demonstrated potential in solving complex many body problems. While a measurement of the full quantum state remains unfeasible, we seek access to partial properties of the density matrix via measurements in random bases using so-called random unitary protocols [1]. We report on the current progress and future prospect of building a fermionic quantum simulator capable of realizing random unitary with high repetition rates and a high-fidelity readout process.
At present, the experiment demonstrates 2D-3D MOT geometry for lithium-6, atom number counting via fluorescence, a molecular BEC, and tweezer loading with 808nm light. The envisaged system offers fast experimental cycles times by loading and evaporative cooling in optical tweezer arrays followed by quantum state assembly in a tunable optical lattice. The readout process aims to reach single site resolution by using matter wave magnification and spin-resolved free-space imaging

References

[1] A. Elben et al, Nature Review Physics **volume 5**, 9-24 (2023)