New Trends in Degenerate Gases: Quantum Computation and Simulation

859. WE-Heraeus-Seminar

21 Jun - 26 Jun 2026

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

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

Aims and scope of the 859. 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 atomic or molecular quantum gases are considered to be ideal both for quantum simulators and quantum computations. Thus, they are best capable to simulate difficult problems in quantum many-body physics as they occur in condensed matter physics and other fields of physics and at the same time allow for developing architectures for quantum computers, which will ultimately surpass classical computers.
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 in 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 E-Mail: axel.pelster@rptu.de
Prof. Dr. Carlos Sá de Melo	Georgia Institute of Technology, Atlanta, USA E-Mail: carlos.sademelo@physics.gatech.edu

Introduction

Administrative Organization:

Dr. Stefan Jorda
Martina Albert

Wilhelm und Else Heraeus-Stiftung
Kurt-Blaum-Platz 1
63450 Hanau, Germany

Phone +49 6181 92325-14
Fax +49 6181 92325-15
E-mail albert@we-heraeus-stiftung.de
Internet: www.we-heraeus-stiftung.de

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

Phone +49 2224 9010-113 or -114 or -117
Fax +49 2224 9010-130
E-mail gomer@pbh.de
Internetwww.pbh.de

Taxi Phone +49 2224 2222

Registration:

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

Program

Program

Sunday, June 21, 2026

17:00 – 21:00	Registration	
18:00 – 21:00	*BUFFET SUPPER and informal get-together*	

Monday, June 22, 2026

07:30	*BREAKFAST*	
08:40 – 09:00	Carlos Sá de Melo	**Opening and Welcome**
Session 1:	**Cavities I**	
09:00 – 09:45	Georg von Freymann	**3D micro-printed potential landscapes for photonic quantum gases**
09:45 – 10:30	Francesco Piazza	**Laser-Painted Cavity-Mediated Interactions in a Quantum Gas**
10:30 – 11:00	*COFFEE BREAK*	
Session 2:	**Kinetic Magnetism**	
11:00 – 11:45	Erich Mueller	**The Geometry of Kinetic Magnetism**
Session 3 :	**Quantum Computation**	
11:45 – 12:30	Jens Eisert	**Fault tolerant quantum computing with cold atoms**
12:30 – 14:00	*LUNCH*	

Program

Monday, June 22, 2026

Session 4:	**Contributed Talks I**	
14:00 – 14:30	Ana Hudomal	**Ergodicity breaking meets criticality in a gauge-theory quantum simulator**
14:30 – 15:00	Lennart Koehn	**Quantum-gas microscopy and Talbot interferometry of the Bose-glass phase**
15:00 – 15:30	Laurent Longchambon	**Route to vortex turbulence in a shell trap**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 18:30	**Plenary Poster Flash Presentations**	
18:30 – 20:00	*DINNER*	
20:00 – 21:30	**Poster Session I** Poster numbers 1 mod 4	

Program

Tuesday, June 23, 2026

08:00	*BREAKFAST*	
Session 5:	**Lattices I**	
09:00 – 09:45	Eugene Demler	**Simulating doped Mott insulators on square and triangular lattices**
09:45 – 10:30	Christof Weitenberg	**Phase microscopes for quantum gases: from weakly to strongly correlated regimes**
10:30 – 11:00	*COFFEE BREAK*	
11 :00 – 11 :45	Imke Schneider	**Tuning Statistics: Multicriticality and Quantum Phases of 1D Lattice Anyons**
Session 6 :	**Quantum Computation, Simulation, and Sensing**	
11:45 – 12:30	Hans Bernien	**Quantum Processors and Quantum Networks – Atom-by-Atom**
12:30 – 12:40	Conference Photo	
12:40 – 14:00	*LUNCH*	
14:00 – 14:45	Monika Aidelsburger	**Many-body quantum dynamics in large-scale, programmable neutral-atom quantum simulators**
14:45 – 15:30	David Spierings van der Walk	**Active and passive control of individual atoms with optical cavities**
15:30 – 16:00	*COFFEE BREAK*	

Program

Tuesday, June 23, 2026

Session 6:	**Quantum Computation, Simulation, and Sensing**	
16:00 – 16:45	Monika Schleier-Smith	**Decoded quantum sensing with cavity-coupled and dipolar spins**
16:45 – 18:15	**Poster Session II** Poster numbers 2 mod 4	
18:30 – 20:00	*DINNER*	
20:00 – 20:15	**Video**	**WEH foundation and its activities**
20:15 – 21:00	Carlos Sá de Melo	**In Memoriam:** **The Legacy of Tony Leggett**

Program

Wednesday, June 24, 2026

08:00	*BREAKFAST*	
Session 7:	**Quantum Simulation**	
09:00 – 09:45	Zala Lenarčič	**Neural networks and generalized Gibbs ensembles for simulation of light-matter coupled systems**
09:45 – 10:30	Thierry Giamarchi	**Quantum transport in cold atomic gases**
10:30 – 11:00	*COFFEE BREAK*	
Session 8:	**Dynamics and Dissipation I**	
11:00 – 11:45	Hui Zhai	**Quantum thermalization dynamics**
11:45 – 12:30	Oded Zilberberg	**Topological classification of quantum driven-dissipative systems**
12:30 – 14:00	*LUNCH*	
14:00 – 18:30	**Excursion**	
18:30 – 20:00	*HERAEUS DINNER* *(social event with cold & warm buffet and complimentary drinks)*	
20:00 – 21:30	**Poster Session III** Poster numbers 3 mod 4	

Program

Thursday, June 25, 2026

08:00 – 09:00	*BREAKFAST*	
Session 9:	**Cavities II**	
09:00 – 09:45	Jean-Philippe Brantut	**Cavity-mediated density-waves in correlated Fermi gases**
09:45 – 10:30	Ana Maria Rey	**S, P, D… BEC… Easy as I, II, III: Pairing games in a cavity**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Peter Domokos	**Collective light scattering from atoms into an optical cavity: subradiance and magic frequencies**
Session 10:	**Supersolidity**	
11:45 – 12:30	Giacomo Valtolina	**New experiments with dysprosium atoms towards cavity-control of dipolar quantum gases**
12:30 – 14:00	*LUNCH*	
14:00 – 14:45	Giovanni Modugno	**Exploring the supersolid phase of matter with quantum gases**
Session 11	**Contributed Talks II**	
14:45 – 15:15	Claudia Politi	**Two-photon cooling of calcium atoms**
15:15 – 15:45	Manfred Mark	**Quantum simulation with dipolar quantum gases**
15:45 – 16:15	Richard Schmidt	**Cold-atom based quantum simulation of excitons in two-dimensional materials**
16:15 – 17:00	*COFFEE BREAK*	
17:00 – 18:30	**Poster Session IV** Poster numbers 4 mod 4	
18:30 – 20:00	*DINNER*	
20:00 -	**Socializing**	

Program

Friday, June 26, 2026

08:00	*BREAKFAST*	
Session 12:	**Dynamics and Dissipation II**	
09:00 – 09:45	Chen-Lung Hung	**Quench dynamics of interacting Bose gases in low dimensions**
09:45 – 10:30	Wei Zhang	**f-Sum rules for dissipative systems**
10:30 – 11:00	*COFFEE BREAK*	
Session13:	**Lattices III**	
11:00 – 11:45	Andrea Bergschneider	**Controlling pair tunnelling in Fermi-Hubbard systems**
11:45 – 12:30	Takeshi Fukuhara (ONLINE via Zoom)	**Quantum simulation of frustrated systems with bosonic atoms in triangular optical lattices**
12:30 – 12:40	Scientific organizers	**Concluding Remarks**
12:40 – 14:00	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday; however, a self-service breakfast will be provided on Saturday morning

Posters

Posters
(Session 1, 2, 3, 4)

Ses. 1 – Mo, June 22 / 20:00 – 21:30 h
Ses. 2 – Tue, June 23 / 16:45 – 18:15 h
Ses. 3 – Wed, June 24 / 20:00 – 21:30 h
Ses. 4 – Thu, June 25 / 17:00 – 18:30 h

1 **Ses. 1**	Mateusz Betke	**Probing particle number fluctuations of a photon Bose-Einstein condensate in a single-shot experiment**
2 **Ses. 2**	Abdelaali Boudjemaa	**Entanglement in two qubits coupled to a reservoir of a Bose-Einstein condensate of microwave-shielded polar molecules**
3 **Ses. 3**	Shane Carter	**Generation and coherent control of many-body spin excitations in a Bose-Einstein condensate via Hamiltonian tuning**
4 **Ses. 4**	Renan da Silva Souza	**Phase transitions of strongly correlated lattice fermions coupled to an optical cavity**
5 **Ses. 1**	Itzal De Urioste Terrazas	**Time-orbiting potential atom chip for guide-wave condensate interferometry**
6 **Ses. 2**	Sudipta Dhar	**Many-body physics with ultracold atoms: from emergent anyons to extended Bose-Hubbard triangular ladder**
7 **Ses. 3**	Luca Donini	**Long-lived state of ultracold bosons in the flat band of an optical kagome lattice**
8 **Ses. 4**	Daniel Dux	**Optical shielding in lithium-6**
9 **Ses. 1**	Karthik Eswaran	**Time quasicrystalline order from periodic driving**
10 **Ses. 2**	Arnaldo Gammal	**Stability of dark solitons in a bubble Bose-Einstein condensate**

Posters
(Session 1, 2, 3, 4)

Ses. 1 – Mo, June 22 / 20:00 – 21:30 h
Ses. 2 – Tue, June 23 / 16:45 – 18:15 h
Ses. 3 – Wed, June 24 / 20:00 – 21:30 h
Ses. 4 – Thu, June 25 / 17:00 – 18:30 h

11 **Ses. 3**	Zachary Gazzillo	**Inverse Supersymmetry in Finite Temperature Bose-Fermi Mixtures**
12 **Ses. 4**	Lakshmi Priyanka Guggilam	**Generation and Transport of K-41 and Rb-87 mixtures in the Einstein-Elevator**
13 **Ses. 1**	Martin Guillot	**Topology in p-band artificial lattices**
14 **Ses. 2**	Soumyadeep Halder	**Dynamical probing of superfluidity and shear rigidity in dipolar Bose-Einstein condensates' phases**
15 **Ses. 3**	Lukas Homeier	**Realizing multi-orbital Emery models with ultracold atoms**
16 **Ses. 4**	Liwia Karakula	**Dynamics of an impurity in a quantum droplet**
17 **Ses. 1**	Nikolai Kaschewski	**Equal-spin and opposite-spin density-density correlations in the BCS-BEC crossover**
18 **Ses. 2**	Elinor Kath	**Extracting spatially-resolved velocity fields of a 2d Bose-Einstein Condensate**
19 **Ses. 3**	Nils Krause	**Damping in open system theory of Bose-Einstein condensates**
20 **Ses. 4**	Joshua Krauß	**On Vortices in Photon Bose-Einstein Condensates: Open-Dissipative Effects on Size and Stability**

Posters
(Session 1, 2, 3, 4)

Ses. 1 – Mo, June 22 / 20:00 – 21:30 h
Ses. 2 – Tue, June 23 / 16:45 – 18:15 h
Ses. 3 – Wed, June 24 / 20:00 – 21:30 h
Ses. 4 – Thu, June 25 / 17:00 – 18:30 h

21 **Ses. 1**	Johann Kroha	**Driven-dissipative dynamics and stabilization of open photon Bose-Einstein condensates**
22 **Ses. 2**	Arpad Kurko	**Collective inhibition of light scattering from atoms into an optical cavity at a magic frequency**
23 **Ses. 3**	Tomasz Wasak	**Beyond single-atom coupling: self-organization through cavity-induced atom-pair interactions in Fermi gas**
24 **Ses. 4**	Louis Lammertyn	**Control and Tomography of Atomic Harmonic Trap-State Synthetic Lattices**
25 **Ses. 1**	Chengshu Li	**Quantum Simulations with Spin-Dependent Rydberg Interaction**
26 **Ses. 2**	Jeffrey Allan Maki	**Pathways to Kondo physics in ytterbium atom chains**
27 **Ses. 3**	Oleksii Malyshev	**Distance learning from projective measurements as an information-geometric probe of many-body physics**
28 **Ses. 4**	Leon Mixa	**The dynamical equilibrium of photon BEC in semiconductor VCSELs**
29 **Ses. 1**	Jonathan Mortlock	**Harnessing ultracold molecules for quantum simulation**
30 **Ses. 2**	Denis Mujo	**Dynamics of dipolar quantum droplets at BEC-quantum droplet crossover**

Posters
(Session 1, 2, 3, 4)

Ses. 1 – Mo, June 22 / 20:00 – 21:30 h
Ses. 2 – Tue, June 23 / 16:45 – 18:15 h
Ses. 3 – Wed, June 24 / 20:00 – 21:30 h
Ses. 4 – Thu, June 25 / 17:00 – 18:30 h

31 **Ses. 3**	Gabriele Natale	**Synchronization of Quasi-Particle Excitations in a Quantum Gas with Cavity-Mediated Interactions**
32 **Ses. 4**	Fengtao Pang	**Bose-Einstein Condensates in a Synthetic Magnetic Field with Tunable Orientation**
33 **Ses. 1**	Michele Pini	**Fate of the Fermi Surface Coupled to a Single-Wave-Vector Cavity Mode**
34 **Ses. 2**	Sayak Ray	**Metastability in Interacting Light–Matter Systems: From Photon BEC to Dicke Superradiance**
35 **Ses. 3**	Sinchan Snigdha Rej	**Neutral atom quantum computation and simulation using EIT based multi-qubit gates**
36 **Ses. 4**	Ritu Ritu	**Thermal amplification and melting of phases in spin–orbit-coupled spin-1 Bose–Einstein condensates**
37 **Ses. 1**	Arko Roy	**Beyond Kibble-Zurek Scaling in Quenched Binary Bose Superfluids**
38 **Ses. 2**	Tingting Shi	**Unambiguous quantum state discrimination in a PT-symmetric system of a single trapped ion**
39 **Ses. 3**	Jonata Soares Santos	**Weakly interacting Bose gas in the canonical ensemble**
40 **Ses. 4**	Morten Strøe	**Investigating Non-Adiabatic Performance in a BEC Quantum Otto Engine**

Posters
(Session 1, 2, 3, 4)
Ses. 1 – Mo, June 22 / 20:00 – 21:30 h
Ses. 2 – Tue, June 23 / 16:45 – 18:15 h
Ses. 3 – Wed, June 24 / 20:00 – 21:30 h
Ses. 4 – Thu, June 25 / 17:00 – 18:30 h

41 **Ses. 1**	Samudra Sur	**Interplay of Noise and Reservoir-induced Decoherence in Persistent Currents**
42 **Ses. 2**	Binhan Tang	**Estimating universal parameters of 1D anyons via Bogoliubov theory**
43 **Ses. 3**	Arina Tashchilina	**Rydberg Physics of Optically Trapped Erbium Atoms**
44 **Ses. 4**	Iris Ulcakar	**Conserved quantities enable the quantum Mpemba effect in weakly open systems**
45 **Ses.1**	Robin Verstraten	**Control of single spin-flips in a Rydberg atomic fractal**
46 **Ses. 2**	Julie Veschambre	**Two-Body Contact Dynamics in a Bose Gas near a Fano-Feshbach Resonance**
47 **Ses. 3**	Botao Wang	**Anyonization of bosons: an effective swap model**
48 **Ses. 4**	Matthias Weidemüller	**Revealing the structure of the heavy Fermi polaron**
49 **Ses.1**	Sarah Wattellier	**Breathing and Fission of Magnetic Multi-solitons**
50 **Ses. 2**	Gianluca Langnese	**Neural network modeling of many-body super- and sub-radiant dynamics**
51 **Ses. 3**	Alexander Wolf	**Mach-Zehnder interferometer for in-situ characterization of atom traps**

Posters
(Session 1, 2, 3, 4)

Ses. 1 – Mo, June 22 / 20:00 – 21:30 h
Ses. 2 – Tue, June 23 / 16:45 – 18:15 h
Ses. 3 – Wed, June 24 / 20:00 – 21:30 h
Ses. 4 – Thu, June 25 / 17:00 – 18:30 h

52 **Ses. 4**	Zeyang Xue	**Microscopy of Light-induced Collective Behaviour in Strongly Interacting Fermi Gases**
53 **Ses. 1**	Yoshihiro Yabuuchi	**Effects of long-range hopping on the stability of current-carrying Bose-condensed states in a hard-core Bose-Hubbard model**
54 **Ses. 2**	Peng Yin	**Dual-species Rydberg arrays for quantum information processing and quantum simulation**
55 **Ses. 3**	Yi-Neng Zhou	**Realizing Unitary k-designs with a Single Quench**

Abstracts of Lectures

(in alphabetical order)

Many-body quantum dynamics in large-scale, programmable neutral-atom quantum simulators

M. Aidelsburger

MPQ/LMU, Munich, Germany

Lattice-based neutral-atom quantum simulators have matured into powerful platforms for the controlled study of strongly correlated many-body systems. With single-site resolution, microscopic control, and system sizes reaching thousands of atoms, they enable studies in regimes that are challenging for classical numerical methods. In this talk, I will highlight recent advances along these directions and illustrate how novel control capabilities open new opportunities for programmable quantum simulation [1,2].

In the first part, I will introduce the subsystem return probability, a quasi-local probe of many-body correlations [3]. Using quantum gas microscopy, we study its short- and long-time dynamics and show that it provides direct experimental access to the dimension of the dynamically accessible Hilbert space, revealing ergodicity breaking via Hilbert-space fragmentation.

In the second part, I will discuss a large-scale realization of a (2+1)D U(1) lattice gauge theory in a bosonic optical superlattice with more than 3,000 sites, and the non-equilibrium preparation of Rokhsar-Kivelson-type quantum spin liquids in a quantum monomer-dimer model [4]. We observe characteristic real-space correlations and momentum-space pinch points of the emergent U(1) gauge structure, and use round-trip interferometric protocols to probe many-body coherence across a region of ~100 lattice sites.

Together, these results establish neutral-atom platforms as versatile tools for exploring strongly correlated, highly entangled quantum matter beyond classically accessible regimes.

References

[1] A. Impertro *et al.*, Phys. Rev. Lett. **133**, 063401 (2024)
[2] A. Impertro *et al.*, Nature Physics **21**, 895-901 (2025)
[3] S. Karch et al., arXiv:2501.16995 (2025)
[4] S. Karch *et al.*, arXiv:2604.24744 (2026)

Controlling pair tunneling in Fermi-Hubbard systems

V. Jonas, H. Zelada, J. Fleper, N. Klemmer, A. Sheikhan, C. Kollath, A. Bergschneider, and M. Köhl

Physikalisches Institut, University of Bonn, D-53115 Bonn, Germany

Quantum simulation of the Fermi Hubbard model plays a central role in studying correlated fermion systems and superconductivity at finite doping. To achieve superconductivity the role of pair dynamics and pair correlations are essential. We investigate systems beyond the repulsive Fermi-Hubbard model towards controlled manipulation of pair-tunneling degrees for freedom.

By extending our optical lattice setup with a superlattice, we gain an additional control parameter that enables us to tune the role of pair tunneling in the system. Using this approach, we recently engineered an effective Hamiltonian with sizeable explicit pair tunneling which usually is exponentially suppress in the simple Hubbard model [1]. These results may bring the realization of novel quantum phases based on pairing mechanisms within reach.

References

[1] Klemmer et al., Phys. Rev. Lett. 133, 253402 (2024)

Quantum Processors and Quantum Networks – Atom-by-Atom

Hannes Bernien – University of Innsbruck & IQOQI, University of Chicago

Reconfigurable arrays of neutral atoms have emerged as a leading platform for quantum science. Their excellent coherence properties combined with programmable Rydberg interactions have led to intriguing observations such as quantum phase transitions, the discovery of quantum many-body scars, and novel quantum computing architectures.

Here, I will look forward to what is next for atom arrays. In particular, I am going to introduce a dual-species Rydberg array, that naturally lends itself for measurement-based protocols such as quantum error correction, long-range entangled state preparation, and measurement-altered many-body dynamics. The second atomic species is used as an auxiliary qubit to measure and control the primary species. In a first demonstration of this architecture, we use an array of cesium qubits to correct correlated phase errors on an array of rubidium data qubits. Rydberg interactions between the two species then lead to novel regimes, including greatly enhanced resonant dipole interactions, that we use to demonstrate a two-qubit gate and quantum non-demolition readout. Finally, we realize quantum cellular automaton dynamics with only global control.

Another crucially important step for atom arrays will be the scaling beyond a single processing module. I will describe how a modular quantum network architecture can look like and will present a node that combines large atom arrays with arrays of photonic interfaces at telecom wavelength.

Cavity-mediated density-waves in correlated Fermi gases

J.P. Brantut

EPFL, Lausanne, Switzerland

Cavity quantum electrodynamics (QED) is one of the most powerful framework to observe and leverage quantum phenomena. While it has been thoroughly studied for simple quantum systems such as two-level systems or harmonic oscillators, it has recently become available for complex, correlated quantum many-body systems. In the last years, we have developed systems combining cavity QED with cold Fermi gases. In such a system, virtual photon exchanges between atoms yield a long-range interaction leading to emergent phenomena.

I will describe how it induces charge-density wave ordering, and the deep insights on this transition provided by real-time measurements and high spatial resolution. I will then discuss the interplay of pairing, Pauli blocking and light-matter interactions in this system, the status of our understanding and some open questions. Last, I will outline the perspective open for quantum simulations in this platform, both from the conceptual and technological point of view.

Simulating Doped Mott Insulators on Square and Triangular Lattices

E. Demler

ETH, Zurich, Switzerland
demlere@phys.ethz.ch

Recent experiments with ultracold atoms have provided new insights into the magnetic properties of doped Fermi-Hubbard models. In this talk, I will review these developments across both square and triangular lattice geometries. For square lattices, recent measurements reveal that a single doping-dependent energy scale governs both the static correlations and the dynamical response of these systems. To explain these findings, I will introduce a self-consistent formalism that captures the coupling between antiferromagnetic magnons and doped holes. Turning to triangular lattices, I will present kinetic magnetism in the strongly interacting regime. I will discuss the magnetic polarons and multi-particle bound states, and discuss how they have been studied using atoms in optical lattices and Rydberg arrays. I will conclude by presenting evidence for a fractionalized phase in the hole-doped SU(4) Fermi-Hubbard model.

Collective light scattering from atoms into an optical cavity: subradiance and magic frequencies

P. Domokos

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

We report on the observation of a new magic frequency within the hyperfine structure of the D2 line of ^{87}Rb atoms at which the scattering of light into a high-finesse cavity is suppressed by an interplay between quantum interference and the strong collective coupling of atoms to the cavity. Scattering from a cloud of laser-driven cold atoms into the cavity was measured in a polarization sensitive way. We have found that both the Rayleigh and Raman scattering processes into the near-resonant cavity modes are extinguished at 185 MHz below the F=2 ↔ F'=3 transition frequency. This coincidence together with the shape of the observed spectral dip imply that the effect relies on a quantum interference in the polariton excitations of the strongly coupled combined atom-photon system. We have also demonstrated the existence of a magic frequency around -506 MHz, where only the Raman scattering is suppressed due to a quantum interference effect at the single-atom level.

[1] Gábor et al. EPJ Quantum Technology (2025) 12:93, https://doi.org/10.1140/epjqt/s40507-025-00401-x

[2] Kurkó et al, arXiv:2601.08978 [quant-ph]

Fault tolerant quantum computing with cold atoms

J. Eisert[1]

[1]*Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany*

For many years, ultracold atoms have been the leading platform for analog quantum simulation. Only relatively recently has it become clear that cold atoms — specifically in optical tweezer arrays — also have the potential to provide one of the most compelling platforms for fault-tolerant quantum computing. This talk will offer a brief introduction to quantum error correction with cold atoms. We will then discuss specific insights into new quantum error-correcting codes tailored to cold-atom architectures [1], enabling highly parallelized quantum logic, as well as associated classical decoding schemes [2]. In an outlook, we will highlight further perspectives and future directions for the field [3].

References

[1] arXiv:2603.05398 (2026).
[2] Nature Comm. 16, 8214 (2025).
[3] Nature Phys., arXiv:2510.19928 (2026).

Quantum Simulation of Frustrated Systems with Bosonic Atoms in Triangular Optical Lattices

T. Fukuhara[1,2]

[1]RIKEN Center for Quantum Computing (RQC), Wako, Japan
[2] Waseda University, Shinjuku, Japan

Magnetic frustration is a central and intriguing theme in condensed matter physics, arising from the competition between interactions and lattice geometry. Even in its simplest form—geometrical frustration in triangular lattices with antiferromagnetic interactions—it gives rise to a rich variety of quantum phases and nontrivial dynamical phenomena.

In this talk, I will present our recent progress in the quantum simulation of frustrated systems using ultracold bosonic atoms. We have developed an experimental platform based on a Bose gas of rubidium atoms loaded into a triangular optical lattice, combined with a quantum gas microscope [1], enabling site-resolved detection with high spatial resolution and sensitivity.

By employing a Bose–Einstein condensate in a periodically shaken triangular optical lattice, we realize an effective frustrated XY model characterized by competing interactions and an emergent two-fold chiral degeneracy of the ground state. Using this system, we investigate relaxation dynamics and excitation processes starting from an initially prepared ferromagnetic state. For rapid parameter ramps, the system frequently populates both ground states simultaneously, which we attribute to the formation of chiral domains. Furthermore, utilizing the quantum gas microscope, we directly detect interference between spatially separated chiral domains, providing insight into domain formation in frustrated many-body systems [2]. These results demonstrate the capability of our platform to probe nonequilibrium dynamics and emergent structures in frustrated quantum systems.

References

[1] R. Yamamoto *et al.*, New J. Phys. **22**, 123028 (2020)
[2] H. Ozawa *et al.*, Phys. Rev. Res. **5**, L042026 (2023).

Quantum transport in cold atomic gases

T. Giamarchi[1]

[1]DQMP, University of Geneva
E-mail: Thierry.Giamarchi@unige.ch

Transport is one of the oldest and most efficient probes in condensed matter, and one of the central ones in what concerns the potential applications of materials. Computing the charge, heat or hall transport of a system placed in between two reservoirs is a very challenging theoretical issue since this is a steady state out of equilibrium problem. This is of course especially true when interactions are present.

Cold atomic gases have provided novel opportunities to study and understand such transport questions, in particular in low dimensional interacting structures.

I will discuss in this talk several transport realizations, and the corresponding methods to compute them, such as the mesoscopic transport of entropy between two reservoirs [1] or the Hall effect in a strongly interacting two leg ladders in synthetic dimensions [2,3].

References

[1] D. Bertolusso, C.J. Bolech, T. Giamarchi, arXiv:2605.00679, (2026).
[2] T.-W. Zhou et al., Nat. Commun. 16, 10247 (2025).
[3] R. Citro, T. Giamarchi, E. Orignac, PRL 134 056501 (2025)

Ergodicity breaking meets criticality in a gauge-theory quantum simulator

Ana Hudomal[1], Aiden Daniel[2], Tiago Santiago do Espirito Santo[3], Milan Kornjača[4], Tommaso Macrì[4], Jad C. Halimeh[5,6,7,8], Guo-Xian Su[9,10], Antun Balaž[1], Zlatko Papić[2]

[1]Institute of Physics Belgrade, University of Belgrade, 11080 Belgrade, Serbia
[2]School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
[3]Federal University of Rio Grande do Norte, 59078-970 Natal, RN, Brazil
[4]QuEra Computing Inc., 1380 Soldiers Field Road, Boston, MA, 02135, USA
[5]Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig Maximilian University of Munich, 80333 Munich, Germany
[6]Max Planck Institute of Quantum Optics, 85748 Garching, Germany
[7]Munich Center for Quantum Science and Technology, 80799 Munich, Germany
[8]Department of Physics, Kyung Hee University, Seoul 02447, Republic of Korea
[9]Department of Physics, MIT, Cambridge, MA 02139, USA
[10]MIT-Harvard Center for Ultracold Atoms, Cambridge, MA 02139, USA

Recent advances in quantum simulations have opened access to the real-time dynamics of lattice gauge theories, providing a new setting to explore how quantum criticality influences thermalization and ergodicity far from equilibrium. Using QuEra's programmable Rydberg atom array, we map out the dynamical phase diagram of the spin-1/2 U(1) quantum link model in one spatial dimension by quenching the fermion mass [1]. We reveal a tunable regime of ergodicity breaking due to quantum many-body scars, manifested as long-lived coherent oscillations that persist across a much broader range of parameters than previously observed, including at the equilibrium phase transition point. We further analyze the electron-positron pairs generated during state preparation via the Kibble-Zurek mechanism, which strongly affect the post-quench dynamics. Our results provide new insights into nonthermal dynamics in lattice gauge theories and establish Rydberg atom arrays as a powerful platform for probing the interplay between ergodicity breaking and quantum criticality.

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Quench Dynamics of Interacting Bose Gases in Low Dimensions

Chen-Lung Hung
Purdue University, West Lafayette, Indiana, USA

Understanding out-of-equilibrium many-body dynamics remains a central challenge in quantum physics. This talk presents two experimental investigations into novel quench dynamics and transport in low-dimensional interacting bosons.

First, I will discuss our investigation of quench dynamics and long-range coherence in quasi-one-dimensional (1D) Bose gases confined in an optical box. While quenches to attractive interactions typically trigger modulational instability and the formation of bright solitons, 1D integrability enables more complex, coherence-preserving "breathing" behavior in long-range density and phase correlations. We report the observation of hydrodynamic shockwaves emerging from an edge-induced "dam break" following an interaction quench. We characterize the novel interplay between these shockwaves and modulational instability seeded from initial bulk density fluctuations, featuring dynamical phase-coherent spatial modulations. Notably, we find that quasi-long-range order can be re-established after a quench back to the repulsive regime, a captivating rephasing process attributed to the nucleation and annihilation of density defects in the quasi-1D geometry.

In a second example, I will discuss the expansion dynamics and quantum self-trapping of strongly interacting bosons in a 2D optical lattice, providing an experimental characterization of the expansion scaling behavior across the superfluid-to-Mott-insulator quantum phase transition. I will discuss how slow expansion manifests in the particle transport near the boundary of an otherwise uniformly distributed, quantum critical 2D Bose gas and present our initial investigation into the expansion of particle- and hole-type density defects on top of a uniform sample.

Quantum-gas microscopy and Talbot interferometry of the Bose-glass phase

L. Koehn,[1,*] C. Parsonage,[1] C. W. Duncan,[1,2] P. Kirton,[1] A. J. Daley,[1,3] T. Hilker,[1] E. Haller,[1] A. La Rooij,[1] and S. Kuhr[1]

[1] *Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK*

[2] *Aegiq Ltd., Cooper Buildings, Arundel Street, Sheffield S1 2NS, UK*

[3] *Department of Physics, University of Oxford, Oxford OX1 3PU, UK*

Quantum-gas microscopes using ultracold atoms in optical lattices offer a powerful platform for quantum simulation with single-atom manipulation and detection capabilities. Using a digital micromirror device (DMD), we create static and dynamic light potentials with single-site resolution [1]. Here, we present our work on disordered systems in which we observe and characterize the Bose-glass phase [2].

The Bose-glass phase is an insulating yet compressible phase that lacks long-range coherence. Using reproducible disorder patterns, we identify the Bose-glass phase through in-situ density distributions and particle-number fluctuations, quantified via the Edwards-Anderson parameter. These measurements are complemented by time-of-flight visibility, allowing us to distinguish the Bose glass from the superfluid phase. Additionally, we probe the coherence length of the systems via Talbot interferometry, revealing a short coherence length on the order of a few lattice spacings in the Bose-glass regime. By driving the system in and out of the Bose-glass phase, we observe non-adiabatic dynamics over experimentally accessible timescales, which we interpret as a signature of the non-ergodic behavior.

Our low-energy studies, combined with Talbot interferometry provide a basis for further exploring disordered systems in and out of equilibrium, such as probing timescales to establish phase coherence. Away from equilibrium, disordered systems undergo many-body localization (MBL), and in future studies we aim to probe the Bose glass and MBL in a single experiment.

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* lennart.koehn@strath.ac.uk

Neural Networks and GGEs for simulation of light-matter coupled systems

I. Ulčakar[1,2], G. Lagnese[1,] and Z. Lenarčič[1],

1 Jožef Stefan Institute, Ljubljana, Slovenia
2 University of Ljubljana, Faculty for mathematics and physics, Ljubljana, Slovenia

Recent advances in quantum simulation are focused on combining matter and light to engineer new types of interactions, possibly characterized by long-range effects and structured dissipation, thus requiring the development of new advanced numerical simulation techniques. For instance, ordered arrays of atoms placed at distances smaller than the wavelength of light display photo-mediated quasi-long-range interactions and a structured correlated emission.

To simulate these dynamics, we employ a numerical approach that combines a positive operator-valued measure (POVM) description of the density matrix—approximated by a neural network—with a time-dependent variational principle (TDVP) to project the evolution of the state onto the neural network manifold. We report the first application of neural quantum states to obtain the dissipative dynamics of light-matter-coupled systems beyond what is accessible with exact and tensor-network calculations in one and two dimension. Numerical result are complemented by a physical interpretation in terms of generalized Gibbs ensembles.

Route to vortex turbulence in a shell trap

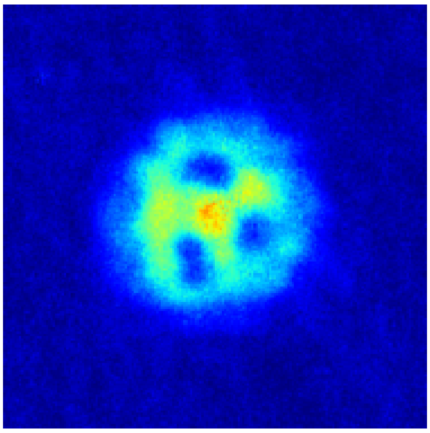
Matthieu Cassus[1], Rishab Sharma[2], Maxime Pesche[2], Laurent Longchambon[1], Thomas Badr[2], Romain Dubessy[3], Hélène Perrin[2]

[1] *Université Sorbonne Paris Nord, LPL, CNRS, UMR 7538, F-93430, Villetaneuse, France*

[2] *CNRS, UMR 7538, LPL, Université Sorbonne Paris Nord, F-93430, Villetaneuse, France*

[3] *Aix-Marseille University, CNRS UMR 7345, PIIM, 13397, Marseille, France*

Recently, the original topology of a Bose–Einstein condensate (BEC) spread onto a closed spherical surface has motivated several theoretical studies. On Earth, to constrain the motion of the atoms to a surface, we make use of adiabatic potentials realized with radio-frequency (rf) dressed ultracold atoms [1]. Thanks to the high degree of control on all parameters they are ideally suited to study superfluid dynamics. In such a trap the inhomogeneity in the rf coupling amplitude results in a force acting against gravity that we can control [2]. When gravity is almost exactly compensated, the pendulum harmonic oscillation at the bottom of the bubble vanishes and the superfluid dynamics become dominated by the quartic term of the potential. We have studied the oscillation of different collective modes in that situation and have evidenced a deviation from the expected frequencies in an harmonic trap beyond the Rotating Wave Approximation. We have also observed the formation of quantized vortices when shaking longitudinally the bubble trap, and have determined a threshold in excitation amplitude for their formation. The onset of vortices from the initial density waves is of particular interest as it sheds a light on how wave turbulence turns into vortex turbulence.



Vortices after shaking the shell trap. Image taken after a 30 ms time-of-flight.

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Quantum simulation with dipolar quantum gases

Manfred J. Mark,[1,2,*] Eva Casotti,[1,2] Clemens Ulm,[1,2] Leonardo Bellinato Giacomelli,[1,2] Andrea Litvinov,[1,2] and Francesca Ferlaino[1,2]

[1] *Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria*
[2] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstr. 21A, 6020 Innsbruck, Austria*

The field of ultracold atomic gases has seen a tremendous evolution over the past 30 years since the first successful creation of a Bose-Einstein condensate in 1995. Such systems offer an unprecedented control over essentially all degrees of freedom, making them an ideal platform for what is now called quantum simulation. The advent of quantum gases made from lanthanide atoms opened up the new field of strongly dipolar systems, as they feature a permanent magnetic dipole moment, giving rise to long-range and anisotropic interactions between the atoms. This type of interaction has proven to be a rich source of new and fascinating many-body phenomena. Here, we first report on the observation of vortices in a rotating two-dimensional supersolid [1]. This counterintuitive state shares solid and superfluid properties at the same time, strongly modifying its behavior under rotation. We additionally observe a synchronization of the crystal's rotation to the external driving frequency triggered by the vortex nucleation, demonstrating the peculiar interplay between superfluidity and crystal structure [2]. This opens up the pathway to study the dynamics of vortices inside the supersolid structure and their modified properties, and to performing quantum simulations of the internal dynsmics of pulsars [3]. We will also give an update about our progress towards a dual-species dipolar quantum gas microscope [4], where we plan to investigate extended Bose- and Fermi-Hubbard based models [5] beyond the capabilities of current setups with short-range interacting atoms.

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* manfred.mark@uibk.ac.at

Exploring the supersolid phase of matter with quantum gases

Giovanni Modugno

LENS and Dipartimento di Fisica e Astronomia, Università di Firenze,
and CNR-INO, Pisa

Supersolids are a fundamental quantum phase of matter combining properties of crystals and of superfluids. Bose-Einstein condensates of strongly magnetic atoms are allowing to study the fundamental properties of supersolids. I will discuss how a supersolid can behave as a self-induced Josephson junction array, and how it is possible to deduce from the Josephson dynamics the superfluid fraction, which is the universal property quantifying the deviation of supersolids from both crystals and superfluids. I will also discuss progresses towards the creation of a supersolid in a ring geometry.

The Geometry of Kinetic Magnetism

Erich J. Mueller

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca NY, USA

Placing a single hard-core fermion on each site of a lattice leads to a highly-degenerate jammed insulating state, where all spin configurations have the same energy. Adding a single mobile hole allows the spins to rearrange themselves, breaking this degeneracy. The resulting magnetic order is referred to as *kinetic magnetism*, as the energy splitting can be attributed to the kinetic energy of the hole. As has been observed in cold atom experiments, these kinetic effects depend on the bandstructure of the lattice. On a square lattice they lead to a maximally polarized ferromagnetic state, where all of the spins align; on a triangular lattice one finds a spin singlet, which can be interpreted as the spins on each of the three sublattices being canted by 120 degrees from one-another. I will describe how the state evolves as one deforms the lattice to interpolate between these two limits. For geometries which are small distortions from the square lattice, we find a phase in which the ferromagnet is stable. For larger distortions the spins instead form a spiral. As one approaches the triangular lattice the pitch of this spiral becomes shorter, eventually becoming the expected 120 degree state. I will also describe finite temperature calculations, where instead of these long-distance spin patterns, one finds a polaron, with strong spin correlations near the hole. We calculate how these spin correlations evolve with temperature and lattice geometry, and how they would appear in an experiment.

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Laser-Painted Cavity-Mediated Interactions in a Quantum Gas

Francesco Piazza
University of Augsburg, Germany

Experimental platforms based on ultracold atomic gases have significantly advanced the quantum simulation of complex systems, yet the exploration of phenomena driven by long-range interactions remains a formidable challenge. For itinerant atoms, currently available methods utilizing dipolar quantum gases or multimode cavities allow us to implement long-range interactions with a $1/r$^3 character or with a spatial profile fixed by the mode structure of the vacuum electromagnetic field surrounding the atoms, respectively. Here, we propose an experimental scheme employing laser-painted cavity-mediated interactions, which enables to realize, for itinerant atoms, interactions that are fully tunable in range, shape, and sign. Our approach combines the versatility of cavity quantum electrodynamics with the precision of laser manipulation, thus providing a highly flexible platform for simulating and understanding long-range interactions in quantum many-body systems. A prominent application will be in the realization of quantum quasicrystal phases, which have so far eluded experimental observation.

Two-Photon Cooling of Calcium Atoms

C. Politi, W. Adamczyk, S. Koch, H. F. Passagem, C. Fischer, P. Filippov, F. Berterottière, J. Urbanetz, D. Kienzler, and J. P. Home

Institute for Quantum Electronics, ETH Zürich, Otto-Stern-Weg 1, 8093 Zurich, Switzerland

Alkaline-earth(-like) atoms trapped in optical tweezers and excited to Rydberg states have emerged as a promising platform for quantum simulation and computation, owing to the high control and scalability of the system. In such systems, the long-lived metastable states can be used for motional ground state cooling, qubit readout and manipulation, as well as providing access to single-photon Rydberg excitation and quantum erasure conversion. To trap individual atoms in optical tweezers, temperatures as low as hundreds of microkelvin are desirable. The absence of hyperfine structure in alkaline-earth atoms precludes the use of standard sub-Doppler schemes developed for alkali atoms. In this work, we demonstrate two-photon cooling of calcium atoms using a two-photon transition from the 1S0 ground state to the upper 4s5s 1S0 state via the 1P1 intermediate state [1]. We achieve temperatures as low as 260 μK in a magneto-optical trap (MOT), well below the Doppler limit (TD = 0.8 mK) of the 1P1 state. This scheme provides an alternative to the standard Doppler cooling applied to alkaline-earth atoms, based on a sequence of two magneto-optical traps, with the advantages of varying the effective linewidth of the 1P1 state, a higher transfer efficiency (close to 100%), and a more straightforward experimental implementation. Finally, we report on trapping calcium atoms in optical tweezers and present our progress toward achieving single-atom occupation.

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S, P, D… BEC… Easy as I, II, III: Pairing Games in a Cavity

Ana Maria Rey
JILA, NIST and University of Colorado, Boulder, CO 80309-0440, USA
Email: arey@jilau1.colorado.edu

Superconductors are defined not just by whether electrons pair, but by how they pair. When multiple pairing symmetries compete, entirely new quantum phases can emerge — including topological states with protected edge currents. Yet in real materials, this competition is notoriously difficult to isolate and control.

In this talk, I will introduce a cavity QED quantum simulator based on ultracold atoms in an optical lattice, where cavity photons mediate long-range interactions whose strength and symmetry can be tuned. Using an Anderson pseudospin mapping, I will explain how to realize superconducting phases with tunable symmetry, from conventional *s*-wave to topological p -wave and d-wave orders. I will also discuss our recent observation of the three dynamical phases of an *s*-wave BCS superconductor and how we directly tracked the order parameter in real time via non-destructive cavity measurements. More broadly, I will explain how this platform establishes a new paradigm for engineering and probing superconductivity in synthetic quantum matter.

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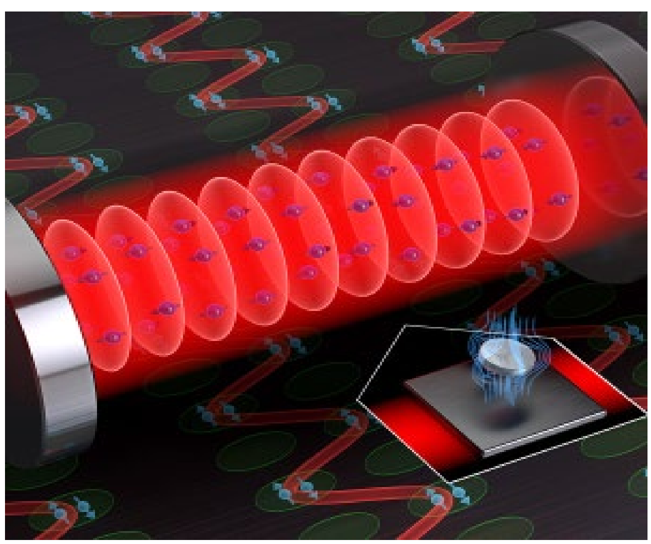

Figure: The dynamic phases of BCS superconductor were observed in a Cavity QED by measuring the light leakage from the cavity

Decoded Quantum Sensing with Cavity-Coupled and Dipolar Spins

M. Schleier-Smith[1]

[1]*Stanford University, Stanford, CA USA*

Entanglement offers a resource for improving precision spectroscopy by enhancing sensitivity to perturbations. A paradigmatic approach is to engineer collective entangled states, such as squeezed states or Schrödinger's cat states, featuring symmetric correlations that enhance the sensitivity to global fields. To expand the impact to a wider range of sensing tasks and targets, we are augmenting this standard toolbox in two complementary directions. On the one hand, converting global entanglement to spatially structured entanglement opens opportunities in multiparameter sensing. We explore this direction in an array of atomic spin ensembles in an optical resonator, where combining the native collective squeezing operations with local optical addressing provides flexibility for engineering the graph of entanglement [1]. In contrast with this highly engineered setting, we alternatively harness the native dipolar interactions in an array of Rydberg atoms to generate Schrödinger-cat-like collective entangled states. In both cases, the same interactions that generate correlations also aid in decoding the interferometric signal. We demonstrate the benefits of such decoding for achieving robustness to detection errors and for accessing nonlocal observables that evade quantum measurement backaction. I will also touch on broader implications of our advances in control of long-range interactions and entanglement for quantum simulation [2] and computation.

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Cold-atom based quantum simulation of excitons in two-dimensional materials

Florian Hirsch and **Richard Schmidt**
Institut für Theoretische Physik, Universität Heidelberg, D-69120 Heidelberg, Germany

Ultracold atoms have emerged as a powerful platform for simulating condensed matter phenomena, offering insights into effects difficult to analyze in detail in solid-state systems. Inspired by the fast progress on the study of exciton physics in atomically thin semiconductors, we investigate how to simulate the physics of excitons in cold atomic systems. In order to directly simulate the physics of the semiconducting class of transition metal dichalcogenides (TMD), we consider single-component fermions comprised of dipolar atoms or molecules placed in a hexagonal optical lattice.

After an introduction to the physics of 2D materials and excitons, in this talk I will show how excitons can be simulated in cold atoms using an energy offset between trigonal sub-lattices that opens up an optical band gap with degeneracies at K/K' points as in two-dimensional materials. Based on a variational approach, we predict the existence of cold atomic excitons comprised of bound atom-hole pairs. We demonstrate how these excitons can be excited using lattice modulation spectroscopy, and show that both time-of-flight spectroscopy and high-resolution quantum gas microscopy can be used to map out the exciton wavefunction. Establishing the core idea of how to simulate semiconductor physics in cold atoms, this lays the foundation for studies of complex electronic states governing semiconductors, including trions, polarons, exciton insulators and condensates.

Tuning Statistics: Multicriticality and Quantum Phases of 1D Lattice Anyons

M. Bonkhoff[1,2], K. Jägering[1], S. Hu[1,3], A. Pelster[1], S. Eggert[1], and I. Schneider[1]

[1]Physics Department and Research Center OPTIMAS, University of Kaiserslautern-Landau, 67663 Kaiserslautern, Germany [2]I. Institut für Theoretische Physik, Universität Hamburg, 22607 Hamburg, Germany [3]Beijing Computational Science Research Center, Beijing 100193, China

Recent advances in quantum technologies enable the realization of synthetic gauge fields and occupation-dependent hopping, allowing for the implementation of “lattice anyons” in one-dimensional systems. These platforms provide a powerful route to explore the interplay between fractional statistics and strong interactions in highly controllable settings, with potential applications in quantum simulation and fault-tolerant quantum information processing.

We investigate the one-dimensional extended Anyon Hubbard model at unit filling using a tailored bosonization approach combined with large-scale numerical simulations. The resulting phase diagram exhibits multiple gapped and superfluid phases, with phase transitions that evolve through a multicritical point as the anyonic exchange phase is tuned from bosonic to fermionic limits. We characterize the associated universality classes and discuss experimentally accessible signatures.

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Active and Passive Control of Individual Atoms with Optical Cavities

David C. Spierings[1,2]
[1] *MIT-Harvard Center for Ultracold Atoms and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Arrays of individually trapped atoms are a promising platform for quantum information processing. Recent progress in this field includes increasing array sizes to thousands of atoms, demonstrating logical quantum operations, and achieving two-qubit gate fidelity exceeding 99.5%. Despite these advances, utility-level atomic quantum processors are expected to require millions of qubits operating under rapid quantum error correction. Optical cavities provide a route to scaling atomic quantum processors while improving system performance.

In this talk, I describe the integration of an optical bow-tie cavity with an array of cesium atoms, enabling a variety of active and passive control techniques. Dispersive light-matter coupling allows fast, nondestructive measurements for observing individual atomic collisions, as well as feedback control of atom number and temperature. Tailored light-matter coupling further supports passive cavity cooling to the atomic ground state and directional control of photon emission through the geometric structure of an atom array or through chiral cavity coupling of a single atom. These works highlight the power of optical cavities for advancing neutral-atom quantum computing while opening new opportunities in fundamental studies of collective, many-body physics.

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New experiments with dysprosium atoms towards cavity-control of dipolar quantum gases

M. Dürbeck[1], L. Reihs[1], J. Seifert[1], B. Choudhari[1], J.P. Marulanda-Serna[1], N. Werum[1], G. Meijer[1], and G. Valtolina[1,2]

[1] *Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany.*

[2] *Humboldt Universität zu Berlin, Newtonstrasse 15, 12489, Berlin, Germany.*

We report on the development of a new experiment for producing mixtures of dysprosium atoms and molecules strongly coupled to an optical cavity, with the ultimate goal of using the cavity fields to control ultracold chemistry. Along this path, we developed a simple laser cooling scheme that allowed us to simultaneously trap two isotopes of dysprosium and realize a new stable and strongly dipolar Bose-Bose mixture in the quantum degenerate regime [1].

In a separate atomic beam experiment, we showed that dysprosium atoms can acquire a large electric dipole moment when prepared in a doublet of opposite-parity excited states, enabling the realization of a unique doubly polar quantum gas [2].

These results may enable the realization of new forms of supersolids.

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3D micro-printed potential landscapes for photonic quantum gases

J. Schulz[1,2], K. Karkihalli Umesh[3], S. Enns[1,2], F. Vewinger[3], and G. von Freymann[1,2,4]

[1] *Department of Physics and Research Center OPTIMAS, RPTU University Kaiserslautern-Landau, Kaiserslautern, Germany*
[2] *Institute of Photonic Systems and Technologies, Leibniz Universität Hannover, Hannover, Germany*
[3] *Institut für Angewandte Physik, Universität Bonn, Bonn, Germany*
[4] *Fraunhofer Institute for Industrial Mathematics ITWM, Kaiserslautern, Germany*

Photonic quantum gases explore the physics of open driven-dissipative quantum systems under ambient conditions and thus open access to thermodynamics and transport phenomena in quantum gases in the weakly interacting regime. In this talk we present the technology of 3D micro-printing [1] to create arbitrary potential landscapes for photonic quantum gases in dye-filled micro cavities (see Fig. 1), which allow to define the potential landscape in which condensation into a common ground state can be analyzed. We realize as a demonstration of the capabilities box potentials with rectangular side walls, anisotropic harmonic potentials, double-well potentials with dimensions on the scale of the wavelength of light as well as potential lattices with topological non-trivial properties.[2] The high fidelity of our approach allows studying the dimensional crossover from 2D to 1D harmonic potentials and the resulting changes in the thermodynamic properties. [3]

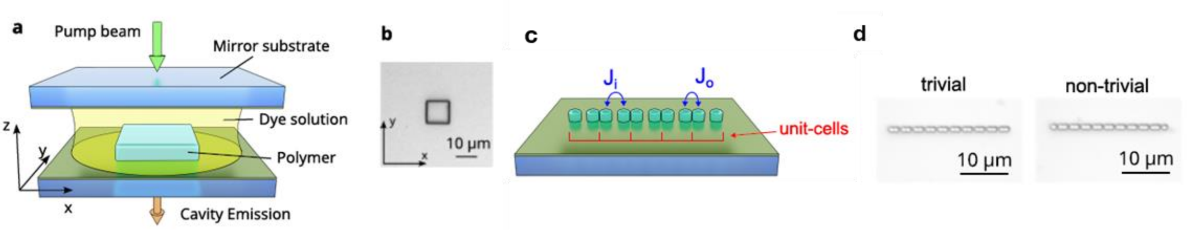

Figure 1. (a) Dye-filled microcavity with printed box potential, (b) microscope image. (c) Sketch of a SSH chain, (d) printed realizations of topological trivial and non-trivial configurations.

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Phase microscopes for quantum gases: from weakly to strongly correlated regimes

C. Weitenberg[1]

[1]Department of Physics, TU Dortmund University, 44227 Dortmund, Germany

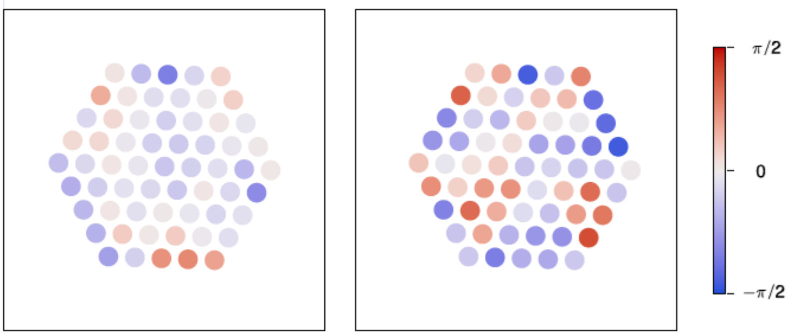

Fig. 1: Phase profiles of a Bose-Einstein condensate in a triangular optical lattice for two different temperatures imaged by the phase microscope.

Quantum gas microscopes probe quantum many-body lattice states via projective measurements in the occupation basis, enabling access to various density and spin correlations. Phase information, however, cannot be directly obtained in these setups. Here I will describe our phase microscope for quantum gases, which measures the local phase profiles with single lattice-site resolution [1], based on Fourier-space manipulation in a matter-wave microscope [2]. We use the phase microscope to study the coherence properties of an ultracold Bose gas in a two-dimensional optical lattice across the thermal phase transition. Furthermore, I will present protocols for a many-body phase microscope, which will give access to various long-range off-diagonal correlators in experimentally realistic settings, which are highly relevant for characterizing many-body phases such as d-wave superconductors or fractional Chern insulators [3]. I will also discuss the idea of a phase-space microscope [4].

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The Kubo-Thermalization Correspondence

Songtao Huang,[1, *] Xingyu Li,[2, *] Jianyi Chen,[1] Alan Tsidilkovski,[1] Gabriel G. T. Assump¸c˜ao,[1] Pengfei Zhang,[3] Hui Zhai,[2, †] and Nir Navon[1, 4, ‡]

[1] *Department of Physics, Yale University, New Haven, Connecticut 06520, USA*

[2] *Institute for Advanced Study, Tsinghua University, Beijing 100084, China*

[3] *Department of Physics, Fudan University, Shanghai 200438, China*

[4] *Yale Quantum Institute, Yale University, New Haven, Connecticut 06520, USA*

Quantum thermalization describes how interacting quantum systems relax toward thermal equilibrium, a central problem in modern physics. Yet most experimental information on many-body systems comes from short-time transition spectroscopy, typically interpreted within Kubo's linear-response framework. These perspectives—long-time equilibration versus short-time response—seem fundamentally disconnected. Here we establish an exact link between them: the *Kubo–Thermalization correspondence*, which connects long-time thermalized populations under weak driving to short-time linear-response spectra for an N-level system coupled to a thermal bath. The correspondence holds even when the steady state differs substantially from the initial state and when each regime is individually difficult to describe theoretically. We experimentally confirm the correspondence using effective spin-1⁄2 impurities realized with ultracold fermions in two internal states coupled to a Fermi sea. Our results provide a rare exact statement about quantum thermalization and offer a novel route to infer thermalization dynamics from equilibrium response measurements in strongly interacting quantum systems, independent of microscopic details of the system–bath coupling.

f-Sum Rules for Dissipative Systems

Xin-Xin Yang ,[1,2] Bo-Hao Wu,[1,2] Yu Chen,[3] and Wei Zhang[1,2,4]

[1]Department of Physics and Beijing Key Laboratory of Opto-electronic Functional Materials and Micro-nano Devices, Renmin University of China, Beijing 100872, China
[2]Key Laboratory of Quantum State Construction and Manipulation (Ministry of Education), Renmin University of China, Beijing 100872, China
[3]Graduate School of China Academy of Engineering Physics, Beijing 100193, China
[4]Beijing Academy of Quantum Information Sciences, Beijing 100872, China

The f-sum rules set general constraints on the response of a quantum many-body system to an external probe and hold significant relevance in the realm of various spectroscopy measurements. In practical conditions, a system unavoidably couples with the environment and acquires effective dissipation. In this Letter, we derive and prove a set of f-sum rules for dissipative systems. Within the framework of linear response theory, we obtain the system response in both linear order of probe field and dissipation parameter. We formulate and prove one first-order and two second-order dissipative f-sum rules. These rules are validated numerically for some example models, and the realization schemes are proposed. In addition, the potential applications are discussed for two interacting many-body systems.

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Flow Topology in Classical and Quantum Driven-Dissipative Systems

G. Villa[1], K. Seibold[1], J. del Pino[3], T. Mutschler[1], M. Mateusz[2], G. Margiani[4], V. Dumont[4] A. Eichler[4] and O. Zilberberg[1]

1 Department of Physics, University of Konstanz, Konstanz, Germany
2 Department of Mathematics, University of Konstanz, Konstanz, Germany
3 Department of Physics, University of Madrid, Madrid, Spain
4 Department of Physics, ETH Zurich, Zürich, Switzerland

In topology, averaging over local geometrical details reveals robust global features. Traditional topological phases of matter focus on linear systems. We establish, instead, a unified framework for the topological classification of driven-dissipative nonlinear systems. To this end, we define a graph index for their Floquet semiclassical equations of motion [1]. This index builds upon the topology of vector flows. It directly encodes the particle-hole nature of excitations around all out-of-equilibrium stationary states, effectively bridging the gap between nonlinear dynamics and established linear topological invariants. Moving on, self-sustained oscillations act as robust organizing centers in phase space limit cycles. We extend the flow topology framework to include limit cycles as fundamental topological elements [2], and map their impact on global flow connectivity. We illustrate this approach with a minimal Van der Pol resonator model (e.g., showcasing competing attractors). There, stable limit cycles coexist with stationary points. Thus, our results provide a unified topological description for both stationary and time-periodic phases. As a next step, we apply flow topology to the quantum regime. Quantum dynamic reorganizations are frequently blurred by density-matrix averaging, where spectral indicators such as the Liouvillian gap can completely miss critical phase transitions that unfold exclusively within the transient evolution. We employ a Lindblad master equation and quantum trajectories to study a driven-dissipative Kerr oscillator [3]. We predict new quantum phases that are not signaled by standard Liouvillian gap closings. The system quantum dynamics retain key topological features of the underlying classical flows. These topological signatures are accessible via (i) quantum state tomography, and (ii) linear response measurements. Consequently, flow topology serves as a powerful tool to identify robust quantum phases.

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Abstracts of Posters

(in alphabetical order)

Probing particle number fluctuations of a photon Bose-Einstein condensate in a single-shot experiment

M. Betke[1], A. Malik[1], A. Bojakowska[1], I. Sankowska[2], A. Broda[2], J. Muszalski[2], T. Czyszanowski[3] and M. Pieczarka[1]

[1]Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland
[2]Institute of Microelectronics and Photonics, Łukasiewicz Research Network, al. Lotników 32/46, 02-668 Warszawa, Poland
[3]Institute of Physics, Lodz University of Technology, ul. Wólczańska 217/221, 93-005 Łódź, Poland

Recent advancements have demonstrated that semiconductor lasers can operate within a near-equilibrium regime characterized by photon Bose-Einstein condensation (BEC) [1]. This state is distinct from traditional lasing, which is fundamentally a non-equilibrium phenomenon, and light thermalization in this regime is expected to exhibit unique physical behaviors [1]. While conventional characterization relies on time-integrated techniques (such as CCD or streak camera imaging) that average out the dynamics of individual events effectively masking the stochastic variations and temporal changes occurring between individual realizations which can give information about statistical ensemble [3], single-shot imaging provides a window into the non-equilibrium effects inherent in microcavities [2]. This approach allows for the direct observation of: self-focusing effects and spatial hole-burning; particle number fluctuations between consecutive, individual realizations of the condensate [2].

In this study, we use an semiconductor optical modulator to isolate individual excitation pulses for our microcavity lasers. By synchronizing the subsequent emission process with EMCCD camera integration, we captured data from distinct, single-shot condensation events and observed spatial and absolute fluctuations of the signal. Our analysis aims to quantify fluctuations in particle number across sequential experimental runs of the photon Bose-Einstein Condensate and also to compare the emission characteristics of microcavities in function of excitation pulse time.

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Entanglement in two qubits coupled to a reservoir of a Bose-Einstein condensate of microwave-shielded polar molecules

Abdelaali Boudjemaa

Department of Physics, Faculty of Exact Sciences and Informatics, Hassiba Benbouali University of Chlef P.O. Box 078, 02000, Ouled Fares, Chlef, Algeria

We study the dynamics of quantum information and entanglement of two distant qubits embedded in a thermal dephasing reservoir consisting of three-dimensional Bose-Einstein condensates of microwave-shielded polar molecules. We calculate the decoherence factors, and the quantum Fisher information in terms of the spatial separation between qubits, and Rabi frequency that tunes the shielding potential. The results show that these quantities are nonmonotonic with revival oscillations at larger separations due to interqubit and qubit-environment correlations. We find also that the shielding interaction may drive the system from the Markovian to the non-Markovian regime enabling us to reach higher values of entanglement.

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Generation and coherent control of many-body spin excitations in a Bose-Einstein condensate via Hamiltonian tuning

Julia T. Cohen, Shane H. Carter, and Michael S. Chapman

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332, USA

Atomic spin-mixing in spinor BECs is a rich phenomenon which has been used to experimentally study squeezed atomic vacuum states, quantum phase transitions, spontaneous symmetry breaking, and analogs of exotic effects from quantum field theory. With the appropriate techniques, spin-mixing can also serve as a powerful tool to manipulate the state of the condensate. We report on experiments in which the interplay between atomic spin-mixing collisions and an external magnetic field is leveraged to demonstrate new methods of quantum control, drawing together ideas from classical Hamiltonian dynamics and many-body quantum systems. We also report on theoretical/numerical investigations into spin-mixing in a multimode context, deriving a relationship between the limits on multimode atomic vacuum squeezing and the spatial mode structure.

Phase transitions of strongly correlated lattice fermions coupled to an optical cavity

Renan da Silva Souza and Walter Hofstetter
Goethe-Universität, Institut für Theoretische Physik, 60438 Frankfurt am Main, Germany

Inspired by the experimental realization of the superradiant self-organization phase transition in ultracold Fermi gases [1], we numerically study a gas of two-component fermions confined to a two-dimensional square optical lattice and coupled to a transversely pumped optical cavity [2]. In the dispersive regime, the steady state of the system is described by an effective extended Hubbard Hamiltonian with cavity-mediated long-range interactions. Using real-space dynamical mean-field theory (RDMFT) [3], we investigate the formation of a (superradiant) checkerboard density-wave phase and its competition with paramagnetic and magnetically ordered phases. At quarter filling, we find a reentrant transition in which a homogeneous Fermi-liquid phase crystallizes into a density-wave phase as the temperature increases, which can be explained by the higher entropy of the density-ordered phase at low temperatures. At half filling, when both the onsite Hubbard interaction and the cavity-mediated long-range interactions are strong, we observe extended regions of the phase diagram where multiple RDMFT solutions are metastable, leading to hysteresis of the density-wave order parameter. In these regions, the density-wave phase coexists with either a Fermi-liquid or a Mott-insulating phase in the paramagnetic case, or with a spin-density-wave phase when magnetic order is allowed. We determine the thermodynamic first-order transition in these regions by comparing the energies of the different RDMFT solutions.

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Time-orbiting potential atom chip for guide-wave condensate interferometry

Itzal De Urioste Terrazas
University of Virginia, USA

Atom interferometers provide a powerful platform for precision inertial sensing, including rotation sensing through the Sagnac effect. Guided-wave interferometry with Bose–Einstein condensates (BECs) offer the potential for long interrogation times and compact device geometries suitable for quantum sensors. We present the design and implementation of a BEC interferometer enabled by a novel cross atom chip that generates a weak AC time-orbiting potential (TOP) trap forming a cylindrically symmetric magnetic waveguide. The chip is operated outside the vacuum chamber near a 1-mm silicon vacuum wall. Atoms are transported near the chip using optical tweezers, where evaporative cooling in a hybrid optical/magnetic trap produces a BEC that is adiabatically transferred into the magnetic waveguide produced by the chip. Bragg pulses are used to coherently split the condensate into counter-propagating matter-wave packets that circulate in the guide and recombine to produce interference fringes detected via absorption imaging. The atom chip is engineered to suppress eddy currents and enable precise control of trap symmetry and anharmonicities, improving stability for guided interferometry. This platform establishes a pathway toward a compact, chip-scale matter-wave gyroscope for quantum inertial sensing.

Many-body physics with ultracold atoms: from emergent anyons to extended Bose-Hubbard triangular ladder

Sudipta Dhar, Milena Horvath,Yanliang Guo, Yi Zeng,Manuele Landini, Hanns-Christoph Nägerl

University of Innsbruck, Institut fur Experimentalphysik, Innsbruck, Austria

Anyons [1,2] are low-dimensional quasiparticles that obey fractional statistics, hence interpolating between bosons and fermions. In two dimensions, they exist as elementary excitations of fractional quantum Hall states and they are believed to enable topological quantum computing. One-dimensional (1D) anyons have been theoretically proposed, but their experimental realization has proven to be difficult. Here, we report the observation [3] of emergent anyonic correlations in a 1D strongly-interacting quantum gas, resulting from the phenomenon of spin-charge separation. A mobile impurity provides the necessary spin degree of freedom to engineer anyonic correlations in the charge sector and simultaneously acts as a probe to reveal these correlations. Starting with bosons, we tune the statistical phase to transmute bosons via anyons to fermions and observe an asymmetric momentum distribution, hallmark of anyonic correlations. Going beyond equilibrium conditions, we observe dynamical fermionization of the anyons, where the momentum distribution of an expanding sample of 1D hardcore anyons following a trap quench becomes indistinguishable from that of a non-interacting, spin-polarized Fermi gas over time, irrespective of the statistical phase. Our work opens up the door to the exploration of non-equilibrium anyonic phenomena in a highly controllable setting.

In the second part, we report our recent effort on the realization of extended Bose-Hubbard model with kHz scale nearest-neighbour interaction in sub-wavelength optical lattices. In particular, we realize a triangular flux ladder using Raman-coupled Cesium atoms in 871-nm anti-magic optical lattice [4]. This opens the route towards the realization of exotic topological phases and phase transitions.

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Long-lived state of ultracold bosons in the flat band of an optical kagome lattice

L. Donini[1], S. Shanokprasith[1], D. Braund[1], T. Marozsak[1], L. Crane[1], M. Barendregt[1,2,3], M. Melchner Von Dydiowa[1,2,3], D.G. Reed[1,4], T. Harte[1], M. Hasan[1,5], and U. Schneider[1]
[1]Cavendish Laboratory, Department of Physics, University of Cambridge, UK
[2]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[3]Munich Center for Quantum Science and Technology, 80799 Munich, Germany
[4]QuEra Computing UK, Harwell Science and Innovation Campus, OX11 0GD, UK
[5]Centre for Cold Matter, Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2AZ, UK

Geometric frustration can give rise to macroscopic ground-state degeneracy and rich physics including exotic new phases of matter. The kagome lattice displays a large degree of frustration, which results in a flat band. For fermions, it makes the kagome Heisenberg antiferromagnet a candidate for studying the quantum spin liquid phase. Even for weakly-interacting scalar bosons, however, the many-body physics in a flat band is complex and not fully understood. In this regime, condensation at high densities is dictated by quantum geometry and an exotic state with three-boson order (a "trion superfluid") is expected at intermediate temperatures and high densities.

Stable loading of ultracold bosons into the flat band of an optical kagome lattice is challenging, as it is not the ground band. We achieve this for the first time by melting an attractive Mott insulator at negative absolute temperature. The state thus prepared occupies predominantly the flat band with a lifetime of many thousands of tunnelling times. It presents non-trivial structure in momentum space, and we use a variety of time-of-flight techniques to characterise it. These include band mapping and Fourier-transforming the momentum distribution to extract real-space correlations. Our experiments naturally realise the regime around unity filling where theoretical understanding remains limited, thus paving the way for further theoretical and experimental studies.

Optical shielding in lithium-6

Daniel Dux [1], Tobias Hammel [1], Maximilian Kaiser [1], Finn Lubenau [1], Matthias Weidemüller [1] and Selim Jochim [1]

[1] Physikalisches Institut Heidelberg, Germany

Email: dux@physi.uni-heidelberg.de

We demonstrate local control of the D2 imaging transition in lithium-6 using a laser beam tuned near the $2p \leftrightarrow 3s$ transition at 813 nm. The diverging polarizability close to this transition produces large shifts of the $2p$ excited-state energy, while the $2s$ ground state remains essentially unaffected, providing direct and differential control over the imaging resonance. The resulting shifts can be made large so that atoms exposed to the shielding beam are detuned far out of resonance with imaging light that is on resonance for unperturbed atoms.

As one application, we use this scheme to locally shield selected atoms during readout. Photon scattering from atoms within the shielding beam is strongly suppressed, while their unshielded neighbours are imaged with full efficiency. In particular, we demonstrate local shielding of the motional ground state, allowing a well-defined initial state to be preserved in part of the system while the remainder is read out.

The same handle, precise control over the excited-state energy with the ground state left essentially intact, enables a broader set of applications that we will show within the Heidelberg Quantum Architecture [1].

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Time quasi-crystalline order from periodic driving

Karthik Eswaran[1,2], Marin Bukov[3], and Krzysztof Sacha[2,4]

[1]Szkoła Doktorska Nauk Ścisłych i Przyrodniczych, Wydział Fizyki, Astronomii i Informatyki Stosowanej, Uniwersytet Jagielloński, ulica Profesora Stanisława Łojasiewicza 11, PL-30-348 Kraków, Poland

[2]Instytut Fizyki Teoretycznej, Wydział Fizyki, Astronomii i Informatyki Stosowanej, Uniwersytet Jagielloński, ulica Profesora Stanisława Łojasiewicza 11, PL-30-348 Kraków, Poland

[3]Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany

[4]Centrum Marka Kaca, Uniwersytet Jagielloński, ulica Profesora Stanisława Łojasiewicza 11, PL-30-348 Kraków, Poland

In analogy to spatial crystals, time crystals can emerge from the self-organization of a system's periodic evolution. Discrete time crystals arise in periodically driven systems, characterized by the emergence of stable evolution with a period that is a multiple of the driving period. Analogously to the formation of quasicrystals in condensed matter physics, periodically driven systems may spontaneously exhibit not only time-crystalline, but also time-quasicrystalline order. We consider a model of coupled p_n, q_n-state chiral quantum clock chains that displays discrete time-translation symmetry breaking by a factor of $p_n q_n$ under periodic kicking. By selecting $\{p_n/q_n\}$ as a sequence of rational approximants of an irrational number, the total system admits discrete time-quasicrystalline order in the limit of large n. These models represent a system in which time-quasicrystalline order arises from an intrinsic Hilbert-space structure, enabling incommensurate responses to a periodic drive, rather than requiring the active imposition of incommensurate frequencies via aperiodic driving. In the sense of symmetry groups, this corresponds to a crossover from the discrete torus $\mathbb{Z}_{p_n} \times \mathbb{Z}_{q_n}$ to $T^2 \cong U(1) \times U(1)$ in the limit of large n. Analytical results for the exactly soluble point of the model and for its robustness in the prethermal sense to small perturbations will be presented. Ongoing matrix product state ansatz numerical calculations relating to the emergence and stability of such order in the general case will also be discussed.

Stability of dark solitons in a bubble Bose-Einstein condensate

Raphael Wictky Sallatti[1], Lauro Tomio[2], Dmitry E. Pelinovsky[3] ,and Arnaldo Gammal[1]

[1]Instituto de Física, Universidade de São Paulo, 05508-090 São Paulo, Brazil
[2] Instituto de Física Teórica, Universidade Estadual Paulista, 01156-970 São Paulo, Brazil
[3]Department of Mathematics, McMaster University, Hamilton, Ontario, L8S 4K1, Canada

The stability of nonlinear waves on curved surfaces is a problem of widespread interest across physics. Here, we establish the stability criteria for dark solitons on a spherical Bose-Einstein condensate. We demonstrate a sharp instability threshold in the nonlinear parameter, beyond which solitons decay into vortex dipoles via snake instabilities. Analytically and numerically, we prove this decay is dictated by a single unstable mode for each angular momentum m >= 2, which is a universal mechanism that controls the resulting vortex state. Unlike in the full three-dimensional case, where snake instabilities lead to vortex rings, a dark soliton confined to the surface of a bubble can only decay into vortex pairs.

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Inverse Supersymmetry in Finite Temperature Bose-Fermi Mixtures

Z. Gazzillo[1] and C. A. R. Sá de Melo[1]

[1]*Georgia Institute of Technology, Atlanta, Georgia, USA*
E-mail: zgazzillo3@gatech.edu

We investigate nearly degenerate Bose-Fermi mixtures and show that the breaking of generalized supersymmetry between bosons and fermions with up to two internal states through the emergence of fermionic Goldstino modes. We draw a distinction between typical supersymmetry (SUSY), where bosons have pseudospin 0 and fermions have pseudospin 1/2, and inverse supersymmetry (iSUSY), where bosons have pseudospin 1/2 and fermions have pseudospin 0. We highlight that the Goldstino pseudospin is carried by either its constituent fermion (SUSY) or boson (iSUSY). We then distinguish between these two cases by depicting their differing effects on the spectral functions of the bosonic and fermionic atomic species. Lastly, we propose an RF-spectroscopy measurement, analogous to momentum (angular) resolved photoemission in condensed matter physics, to measure the pseudospin-dependent spectral functions and detect the emergence of Goldstino modes in mixtures of ^{39}K and ^{40}K.

Generation and Transport of K-41 and Rb-87 mixtures in the Einstein-Elevator

G.L. Priyanka[1] , J. Böhm[1] , D. Leopoldt[1] , B. Piest[2] , Annie Pichery[2] , Timothé Estrampes[1] , Naceur Gaaloul [1] ,E.M. Rasel [1] and the MAIUS Team[1,3,4,5,6,7]

[1] Institut für Quantenoptik, LU Hannover - [2] LTE, Observatoire de Paris, France- [3]ZARM, Uni Bremen -[4]FBH Berlin - [5]DLR Institut für Raumfahrtsysteme, Bremen-[6] Institut für Physik, HU Berlin - [7] Institut für Quantenoptik, Universität Mainz

The successful creation of the first BEC in space (MAIUS-1) demonstrated the viability of matter-wave interferometry for precision physics [1], specifically for testing Einstein's Equivalence Principle (EEP). The successor apparatus MAIUS-B [2] targets dual-species interferometry using K-41 and Rb-87. Flown on a sounding rocket in December 2023, it is now transformed into a drop tower experiment in the Einstein-Elevator facility (Hannover) which provides 4 seconds of microgravity every 4 minutes.

In this talk, I will report on the experiments conducted in this drop tower, focusing on the optimization of sympathetic cooling sequences required to achieve dual degeneracy in this unique environment and on the observation of the symmetric ground state of quantum mixtures which is possible only in microgravity [3]. Furthermore, the results demonstrating the efficient simultaneous transport of the mixture using Shortcut To Adiabaticity (STA) protocols will also be presented, establishing the necessary prerequisites for high-precision EEP tests on atom chips in space.

This work is now funded by the German Research Foundation (DFG) within the framework of the Excellence Strategy of the Federal and State Governments – EXC 2123/2 Quantum Frontiers – 390837967

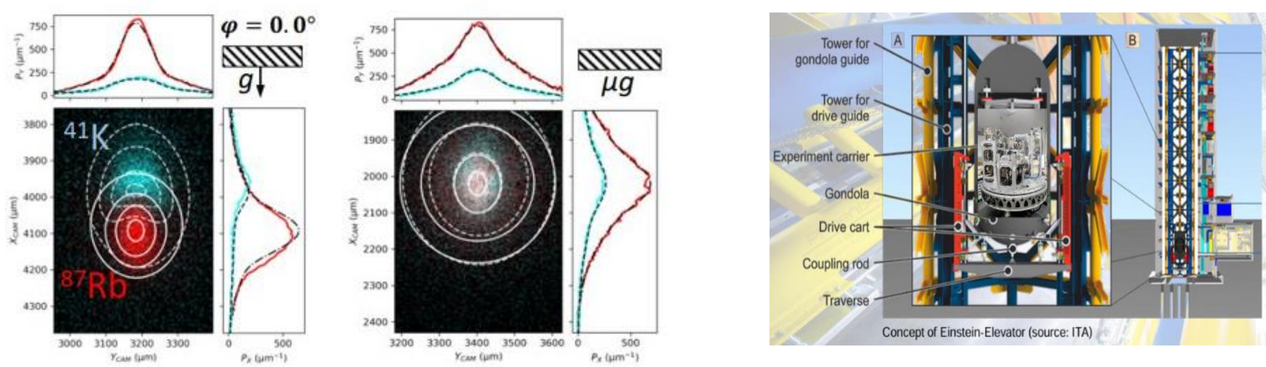

Fig 1. (left and middle) show the simulated and observed quantum mixture ensembles on ground and in microgravity [3]. (right) is the Einstein-Elevator facility with MAIUS-B inside the gondola.

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Topology in p-band artificial lattices

Martin Guillot[1,2], Cédric Blanchard[1], Martina Morassi[1], Aristide Lemaître[1], Luc Le Gratiet[1], Abdelmounaim Harouri[1], Isabelle Sagnes[1], Robert-Jan Slager[3,4], F. Nur Ünal[3,5], Jacqueline Bloch[1], Sylvain Ravets[1]

[1] TU-Dortmund, Otto-Hahn Str. 4a, 44227 Dortmund, Germany
[2] Center for Nanoscience and Nanotechnology, CNRS, Paris-Saclay university, 91120 Palaiseau, France
[3] TCM Group, Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, United Kingdom
[4] Department of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, United Kingdom
[5] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, United Kingdom
martin.guillot@tu-dortmund.de

Modern condensed matter physics has highlighted the role of crystal orbital symmetries in understanding the electronic properties of solids. While two-band systems are heavily employed in the framework of Chern topology, many physical systems possess multiple bands and exhibit phenomenology reaching beyond previously known classifications (Bouhon et al. 2020). Notably, semimetallic multi-gap systems feature band singularities carrying non-Abelian charges with braiding properties, which have been shown theoretically to be responsible for the nonzero superfluid weight of the flat band in twisted bilayer graphene (Xie et al. 2020). While the theoretical exploration of such phases is underway, a matching experimental exploration is lacking, due to the complexity in the creation and probing of such phases. In this pursuit, p-like orbitals provide a promising direction, as they are expected to host a wide range of phenomena while allowing more straightforward band engineering than s-type band structures with a comparable number of bands. In this poster, I will present the direct measurement of the non-Abelian quantum geometric tensor (QGT) we achieved by implementing a novel orbital-resolved polarimetry technique to probe the full Bloch Hamiltonian of a six-band two-dimensional (2D) polaritonic lattice. This technique grants direct experimental access to non-Abelian quaternion charges, the Euler curvature, and the non-Abelian quantum metric associated with all bands. Furthermore, I will outline how this work might lead to the implementation of novel topological phases in cold-atom optical lattices.

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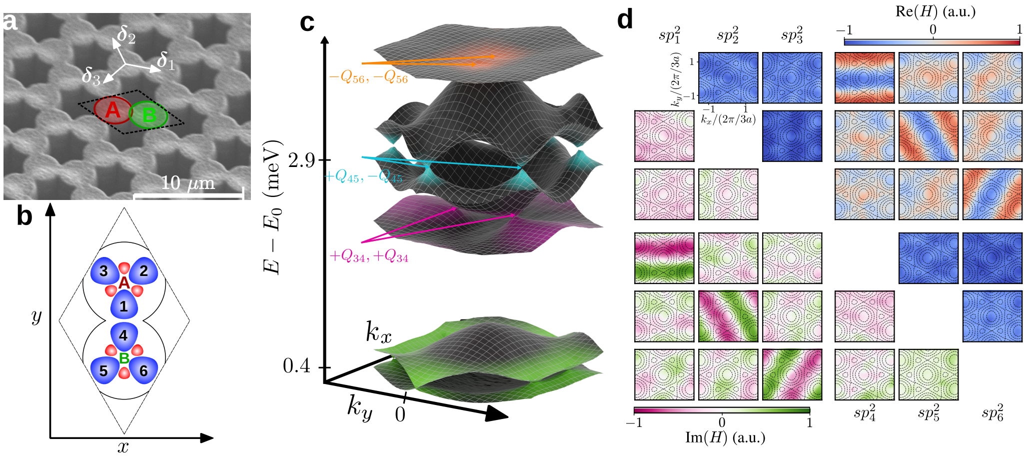

Figure 1: **a**. Scanning electron microscope image of the honeycomb lattice used in this work. **b**. Representation of the lattice unit cell showing the $|sp^2\rangle$ modes with positive (negative) lobes in blue (red) color. **c**. Measured band dispersion. Arrows point toward the different nodes in the p-bands. We also indicate their measured topological charges. **d**. Reconstruction of the $\boldsymbol{k}$-dependent off-diagonal matrix elements of the Hamiltonian in the $\{|sp^2_\sigma\rangle\}$ basis. Each plot shows the real (upper triangle) and imaginary (lower triangle) part of one of the Hamiltonian components, as a function of k_x and k_y. In each panel, dashed lines show iso-energy contours of the difference between bands 5 and 4.

Dynamical probing of superfluidity and shear rigidity in dipolar Bose-Einstein condensates' phases

Soumyadeep Halder[1], Hari Sadhan Ghosh[2], Axel Pelster[3], and B. Prasanna Venkatesh[1]

[1]Department of Physics, Indian Institute of Technology Gandhinagar, Gujarat 382055, India
[2]Department of Physics, Indian Institute of Technology Kharagpur, Kharagpur 721302, India
[3]Department of Physics and Research Center OPTIMAS, RPTU Kaiserslautern-Landau, Kaiserslautern, Germany

We show that a sudden change in the polarization direction of the magnetic dipole moments of the atoms in a dipolar Bose-Einstein condensate (BEC) can serve as a useful probe to sense its superfluid and solid-like properties. We find that for small angular deviation of the polarization direction, actuated for instance by modifying an external magnetic field, the superfluid state undergoes an undamped scissors mode oscillation, a characteristic signature of superfluidity. In contrast, both the droplet and supersolid states exhibit a damped scissors-mode oscillation and eventually orient along the final altered polarization direction. Notably, we find that this damping rate provides a qualitative measure of the rigidity of different phases of a dipolar BEC. Furthermore, there exists a maximum angular deviation of the polarization direction, beyond which the droplet and the supersolid states undergo a permanent deformation i.e., we find an analog of the usual elastic to plastic phase transition of solids.

Title: Realizing multi-orbital Emery models with ultracold atoms

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Abstract: Strongly-correlated electrons in transition-metal oxides give rise to intriguing emergent phenomena, including high-temperature superconductivity in cuprates. While simplified one-band Hubbard models capture some aspects, explicitly describing the interplay of copper and oxygen orbitals -- as in the three-band Emery model -- is essential to capture the full phenomenology of cuprates. Quantum simulators based on ultracold atoms offer a promising route to study such systems in a controlled setting, but realizing realistic multi-orbital Hubbard models remains challenging. Here we propose an optical superlattice architecture that implements the three-band Emery model with ultracold fermions. By combining lattice beams with controllable interference, we engineer orbital degrees of freedom that reproduce key features of the cuprate band structure, while enabling independent control of orbital-dependent interactions and charge-transfer energy. We show that single-particle quantum walks can benchmark the resulting tight-binding model. Using determinant quantum Monte Carlo, we further investigate thermodynamic properties in the undoped regime and find a finite-temperature metal-insulator crossover accompanied by the onset of antiferromagnetic correlations accessible in current experiments. Our results provide a practical pathway to simulate multi-orbital Hubbard physics with quantum gas microscopes.

Conall McCabe, Jamie Boyd, Kaizhao Wang, Martin Lebrat, Cindy Regal, Adam M. Kaufman, Ana Maria Rey, **Lukas Homeier**

JILA, National Institute of Standards and Technology, Center for Theory of Quantum Matter, and Department of Physics, University of Colorado, Boulder, CO, 80309, USA

Dynamics of an impurity in a quantum droplet

Liwia Karakula[1], Piotr Wysocki[2,3], Marek Tylutki[4], Krzysztof Jachymski[1]

[1] Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland
[2] Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria
[3] Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria
[4] Institute of Theoretical Physics, Wrocław University of Science and Technology, 50-370 Wrocław, Poland

Characterizing the behaviour of an impurity embedded in a quantum medium is essential for understanding emergent many-body phenomena and for developing future quantum technologies. In ultracold atomic gases, beyond-mean-field effects can significantly modify impurity dynamics. In this work, we investigate the motion of a single impurity immersed in a quantum droplet and compare it to the case of a Bose–Einstein condensate. Using modified Gross–Pitaevskii equation that incorporates the Lee–Huang–Yang correction, together with the Lee–Low–Pines transformation to the co-moving frame, we simulate the impurity–medium dynamics in various scenarios. We extract the static properties of the system as well as the effective mass of the polaron. The balance between attractive and repulsive forces in the droplet leads to qualitatively different behaviour compared to the standard condensate, including modified excitation patterns and changes in the impurity's dressing by the background atoms.

Equal-spin and opposite-spin density-density correlations in the BCS-BEC crossover

N. Kaschewski[1], **A. Pelster[1] and C. A. R. Sá de Melo[2]**

[1]Department of Physics and Research Center OPTIMAS
RPTU Kaiserslautern-Landau, Germany
[2] School of Physics, Georgia Institute of Technology, Atlanta, USA
E-mail: kaschews@rptu.de

For cold atomic gases in the superfluid state, it has been predicted already two decades ago by Quantum Monte Carlo (QMC) methods, that the opposite-spin density-density correlation function in 3D shows a reduction below the uncorrelated value of unity for intermediate distances [1]. Recent experimental developments resulted in the development of the continuous quantum gas microscope [2-5], allowing for a direct measurement of pair correlations in 2D. The measurements revealed [5] what was already predicted using QMC methods [1], a drop of the anomalous pair correlation below the background value of one, sparking new interest into this phenomenon, which lacks an analytical explanation.

Inspired by this development, this poster presents a general theory of spin-dependent density-density correlations, that is valid for any temperature, interactions, dimensions and mass or population status of Fermi gases with two internal states [6]. We use gauge invariance and the Pauli principle to establish constraints on the spin-dependent density-density correlations that are consistent with the fluctuation-dissipation and Wick's theorem. As an example, we study the spin-dependent density-density correlations from the BCS to the Bose regime in two dimensions at zero temperature, inspired by experiments in ^{6}Li. We show that two-particle irreducible contributions, involving collective excitations, many-particle scattering and vertex corrections, are essential to describe experiments. In particular, the two-particle irreducible terms are responsible for the emergence of an experimentally observed minimum in the opposite-spin density-density correlations.

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Extracting spatially-resolved velocity fields of a 2d Bose-Einstein Condensate

•Elinor Kath, Jelte Duchene, Hanyi Jang, Floriane Arrouas, Helmut Strobel, and Markus K. Oberthaler — Kirchhoff-Institut für Physik, Universität Heidelberg

In a superfluid, many dynamical processes, such as transport mechanisms or turbulent flow patterns, remain hidden in density images, but would be directly observable in the superfluid's velocity field. However, directly measuring the velocity field of a Bose–Einstein condensate is not straight-forward experimentally.

We developed a method to extract spatially resolved velocity fields from a single experimental realisation of a 2d Bose-Einstein condensate. The technique is based on Bragg scattering, where a lattice potential velocity-selectively transfers momentum to atoms. After a short time-of-flight, the boosted atoms separate spatially from the main cloud and can be imaged with standard techniques. With the information encoded in the scattered-out clouds the superfluid's velocity field can be reconstructed.

In this contribution, we will report on benchmarking the technique with the velocity profile of a superfluid vortex. Building on this new technique we are able to observe transport processes in a turbulent superfluid having access to the full velocity field. This allows us to determine the system’s kinetic energy distribution in the compressible and incompressible components. Analysing their spatial structure and temporal evolution provides insight into how energy is redistributed across the system and between these channels as the system evolves towards equilibrium.

Damping in open system theory of Bose-Einstein condensates

Nils A. Krause[1,2] and Ashton S. Bradley[1,2]

[1]Department of physics, University of Otago, Dunedin, New Zealand
[2]Dodd-Walls Centre for Photonic and Quantum Technologies, Dunedin, New Zealand

We investigate damping mechanisms in the open quantum system description of Bose-Einstein condensates. Dividing the gas into a coherent (C) and incoherent (I) region we consider the stochastic projected Gross-Pitaevskii equation (SPGPE) that features three distinct damping mechanisms. Number damping (corresponding to the simple growth SPGPE) describes the growth of the C region by particles from the I region. It has proven to give excellent equilibrium results and has been used for initial state preparations. Applied on dynamical problems it can describe qualitative features. However, it fails in providing a quantitatively accurate description of decay. Another decay channel, energy damping, stems from the number conserving scattering between C and I region particles. Our analysis demonstrates that for high phase space density it dominates over number damping [1] and might hence explain the discrepancies. Finally, we derive the so-far neglected evaporative damping [2], caused by the evaporation of particles from the C into the I region. We argue that this process is often comparable in magnitude to number damping.

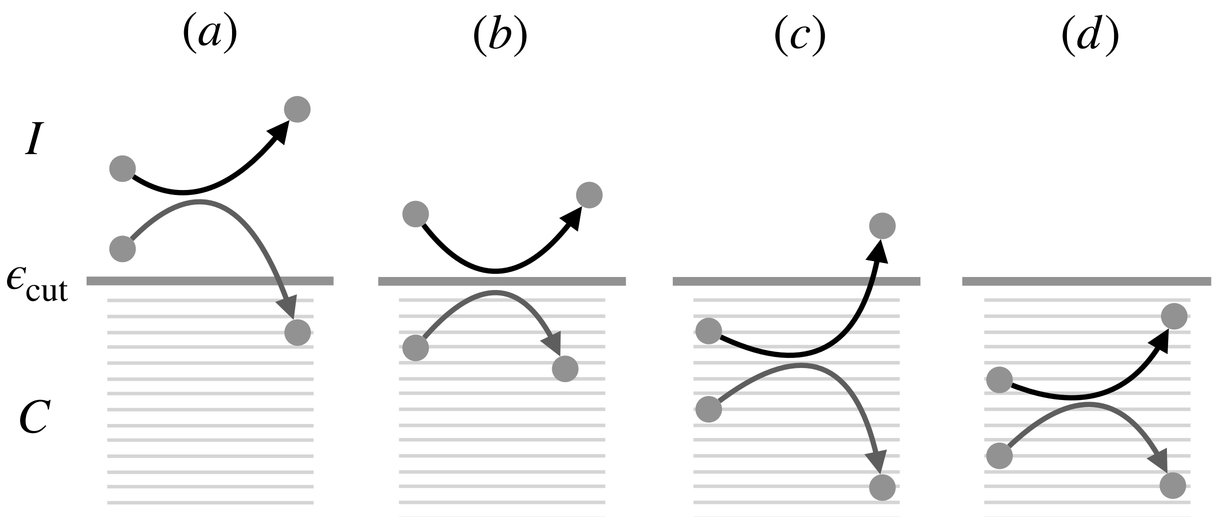

Fig. 1: The different possible scattering events in the SPGPE. (d) corresponds to the Hamiltonian non-linear interaction, while (a)-(c) stem from the interaction with the I region: (a) number damping, (b) energy damping, (c) evaporative damping.

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On Vortices in Photon Bose-Einstein Condensates: Open-Dissipative Effects on Size and Stability

Joshua Krauß [1], **F. Ednilson A. dos Santos [2] and Axel Pelster [1]**

[1] *Physics Department and Research Center OPTIMAS, University Kaiserslautern-Landau, Erwin-Schrödinger Straße 46, 67663 Kaiserslautern, Germany*
[2] *Departamento de Física, Universidade Federal de São Carlos, São Carlos, São Paulo, 13565-905, Brazil*

Open-dissipative quantum fluids have been extensively studied numerically [1,2]. In view of a complementary analytical description, a recent study [3] introduced the projection optimization method, generalizing the standard optimization method for closed condensates [4] to open-dissipative systems. We apply this method to a complex Gross-Pitaevskii equation [5] that heuristically models a photon Bose-Einstein condensate, which is harmonically trapped. Together with established methods from hydrodynamics, we obtain an approximate dynamical vortex solution and demonstrate how open-dissipative parameters affect both vortex size and stability.

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Driven-dissipative dynamics and stabilization of open photon Bose-Einstein condensates

R. Kramer[1], M. Janning[1], M. Turaev[1], S. Ray[1,2] Johann Kroha[1,3]

[1] Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany
[2] Fachbereich Physik, RPTU Kaiserslautern-Landau, Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany
[2] School of Physics and Astronomy, University of St Andrews, North Haugh, St. Andrews, KY16 9SS, United Kingdom
Emai: jkroha@uni-bonn.de

The recently observed Bose-Einstein condensate of photons realized in a dye-filled optical micro-resonator [1] has become a platform to study various nonequilibrium phenomena. Due to the driven-dissipative nature of the photon gas, the condensate is prone to decay in the long-time limit due to incoherent processes arising from, for instance, non-condensed photon fluctuations. In the previous study [2], we in vestigated the resulting dynamics using the Markovian rate equation approach including fluctuations, and discovered a new mechanism of dynamical stabilization based on a ghost attractor, a physically inaccessible fixed point lying outside the physical realm which nevertheless attracts the dynamics and leads to aplateau-like stabilization of the condensate density for an exponentially long time. Despite the nonequilibrium origin of this dynamical stabilization, the condensate exhibits quasithermal fluctuations in the plateau [3]. In recent and ongoing studies, we have found signatures of this extremely slow relaxation directly in the Liouvillian spectrum of the full quantum master equation obtained via exact diagonalization. The presence of a near-zero Liouvillian eigenvalue confirms the slow dynamics predicted by the rate-equation analysis.

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Collective inhibition of light scattering from atoms into an optical cavity at a magic frequency

Á. Kurkó[1], B. Gábor[1,2], D. Varga[1,3], A. Simon[1,3], T. Barmashova[1], A. Dombi[1], T. W. Clark[1], F. I. B. Williams[1], D. Nagy[1], A. Vukics[1], P. Domokos[1,4]

[1] *HUN-REN Wigner RCP, H-1525 Budapest P.O. Box 49, Hungary*
[2] *Department of Theoretical Physics, University of Szeged, Tisza Lajos körút 84, H-6720 Szeged, Hungary*
[3] *Department of Physics of Complex Systems, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/A, H-1117 Budapest, Hungary*
[4] *Institute of Physics, Budapest University of Technology and Economics, H-1111 Budapest, Műegyetem rkp. 3, Hungary*

We report on the observation of a new magic frequency within the hyperfine structure of the D_2 line of ^{87}Rb atoms at which the scattering of light into a high-finesse cavity is suppressed by an interplay between quantum interference and the strong collective coupling of atoms to the cavity [1]. We measured the polarization-resolved scattering from a cloud of laser-driven cold atoms into the cavity, finding that both the Rayleigh and Raman scattering processes into the near-resonant cavity modes are extinguished at 185 MHz below the F=2↔F'=3 transition frequency, see the dip indicated by the red arrow in fig. 1. This coincidence together with the shape of the observed spectral dip imply that the effect relies on a quantum interference in the polariton excitations of the strongly coupled combined atom-photon system. We have also demonstrated the existence of a magic frequency around -506 MHz, where only the Raman scattering is suppressed due to a quantum interference effect at the single-atom level.

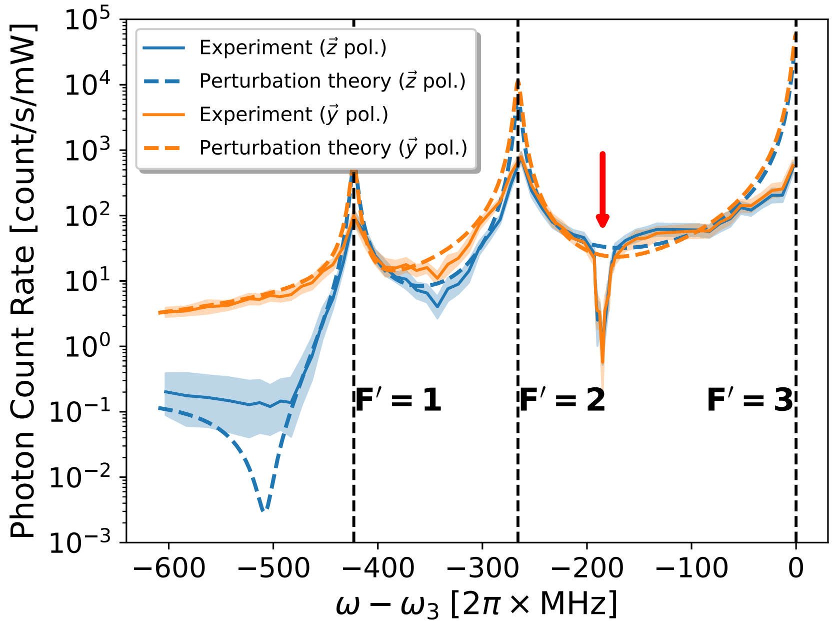

Figure 1: Polarization-resolved photon count rates normalized to the input power as a function of the drive detuning. The measurement data (solid lines with shaded area representing the standard deviation of 100 measurements) are compared with the single-atom scattering rate model (dashed line). Vertical dashed lines indicate the transition resonances to excited hyperfine states. The arrow indicates the collective inhibition of scattering at the magic frequency.

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Neural network modeling of many-body super- and sub-radiant dynamics

Gianluca Lagnese[1], **Laurin Brunner**[2], **Lorenzo Rossi**[3], **Darrick E. Cheng**[3,4], **Markus Schmitt**[5], **and Zala Lenarčič**[1]

[1]*(Presenting author underlined) Jožef Stefan Institute, 1000 Ljubljana, Slovenia*
[2]*Theoretical Physics III, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, D-86135 Augsburg, Germany*
[3] *ICFO—Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Spain*
[4] *ICREA—Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain*
[5] *Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Quantum Control (PGI-8), 52425 Jülich, Germany*

Recent advances in quantum simulation are focused on combining matter and light to engineer new types of interactions, typically characterized by long-range effects, requiring the development of advanced numerical simulation techniques. For instance, ordered arrays of atoms placed at distances smaller than the wavelength of light display photo-mediated long-range dipole-dipole interactions and a peculiar correlated emission. The main features observed when starting from a highly excited initial state are a superradiant burst at short times, followed by a non-trivial "subradiant" critical regime with a slow power-law relaxation [2]. By integrating out the photonic degrees of freedom, the dynamics are effectively described by a Lindblad equation with long-range interactions and dissipation. To simulate these dynamics, we employ a recently proposed numerical approach [1] that combines a positive operator-valued measure (POVM) description of the density matrix — approximated by a neural network — with a time-dependent variational principle (TDVP) to project the evolution of the state onto the neural network manifold. We explore upscaling to larger system sizes as a complementary tool to standard tensor network techniques, especially for long-range interactions and two-dimensional setups. From a more physical perspective, by applying a time-dependent Generalized Gibbs Ensemble Ansatz, we uncover the role of (approximate) integrability at long times, which leads to the observed polynomial decay.

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Control and Tomography of Atomic Harmonic Trap-State Synthetic Lattices

A. Shankar[1], L. Lammertyn[2], S. Van Wellen[2], K. Van Acoleyen[1,2]

[1] Faculty of Science, Department of Physics and Astronomy, Ghent University, Krijgslaan 299, Ghent, Belgium

[2] Faculty of Engineering Technology, Department ELIS, Ghent University, Krijgslaan 297, Ghent, Belgium

The realization of synthetic dimensions using atomic harmonic trap states provides a highly tunable platform for quantum simulation. While early experiments established this mapping through observations of single-particle Bloch oscillations, fully exploiting the platform requires both arbitrary control over lattice connectivity and robust state characterization. Here, we significantly extend the capabilities of trap-state synthetic dimensions in these directions. We implement a multi-tone periodic driving scheme that enables programmable hopping amplitudes and synthetic gauge phases. We further introduce a robust measurement protocol for the synthetic center-of-mass motion that leverages the phase-space rotation of the harmonic trap, avoiding the assumptions underlying previous imaging techniques. Finally, we develop and experimentally validate a state tomography protocol that reconstructs the single-particle density matrix in the synthetic basis, resolving both diagonal populations and off-diagonal coherences. Together, these advances establish atomic trap-state synthetic dimensions as a versatile platform for quantum simulation of non-equilibrium dynamics and complex lattice models.

Quantum Simulations with Spin-Dependent Rydberg Interaction

Chengshu Li and Hui Zhai

Institute for Advanced Study, Tsinghua University, Beijing 100084, China

Exploiting the rich atomic physics of Rydberg atoms assembled in an array has led to prolific opportunities in the quantum simulation of many-body physics. In this work, we propose a novel setup that realizes spin-exchange interaction. Unlike previous setups, we use exclusively s-orbit states, and therefore the exchange anisotropy is completely determined by the spatial orientation. This allows a native realization of the Kitaev–Heisenberg model. The ground state phase diagram has singlet-product phases and symmetry-breaking stripe phases, the latter not realized in experiments before. Our results establish the setup as a unique platform for space-anisotropic exchange interaction and open a new avenue of quantum many-body physics research with Rydberg atom arrays.

Pathways to Kondo physics in ytterbium atom chains

Jeff Maki[1], * Lidia Stocker[2], and Oded Zilberberg[1]
[1]Department of Physics, University of Konstanz, 78464, Konstanz, Germany
[2]Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany

The Kondo effect is a paradigmatic model of strongly-correlated physics, where a magnetic impurity forms a many-body singlet with a fermionic environment. The properties of this singlet depend sensitively on correlations within the host system, which are particularly pronounced in one dimension, where interactions give rise to Luttinger liquid behavior. A promising platform to study these effects is provided by cold gases of ytterbium (Yb), where an atomic impurity is coupled to an interacting one-dimensional fermionic environment via both magnetic and potential scattering. These two scattering mechanisms compete with each other, raising the question of how robust Kondo screening remains in such systems. Here, we show that potential scattering can suppress Kondo screening in one-dimensional Yb gases. Remarkably, however, Kondo physics persists in well-defined regimes determined by the interactions in the environment. Combining analytical renormalization-group methods with density matrix renormalization group (DMRG) simulations, we identify a transition from a strongly to a weakly entangled impurity as potential scattering increases. The two approaches are in excellent agreement across the parameter regimes considered. Our results provide a quantitative criterion for the emergence of Kondo screening in one-dimensional Yb gases and delineate experimentally accessible regimes for its realization in cold-atom platforms.

Distance learning from projective measurements as an information-geometric probe of many-body physics

Oleksii Malyshev[1], Simon M. Linsel[2,3], Fabian Grusdt[2,3], Annabelle Bohrdt[2,3], Eugene Demler[1], Ivan Morera[1]

[1] Institute for Theoretical Physics, ETH Zürich, CH-8093 Zürich, Switzerland
[2] Department of Physics and Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 München, Germany
[3] Munich Center for Quantum Science and Technology, Schellingstr. 4, D-80799 München, Germany

The ability of modern quantum simulators—both digital and analogue—to generate large ensembles of single-shot projective "snapshots" has opened a data-rich avenue for the study of quantum many-body systems [1,2]. Unsupervised machine learning analysis of such snapshots has gained traction, with numerous works reconstructing phase diagrams by learning and clustering low-dimensional representations of quantum states [3–5]. Here, we forgo such representation learning in favour of *distance* learning: we infer the pairwise distances between quantum states—already sufficient for clustering—directly from snapshots. Specifically, we use a single neural discriminator to estimate Csiszár f-divergences—statistical distances between distributions [6]—in an unsupervised manner. The resulting clusters reveal regimes with different dominant correlations, often coinciding with, but not limited to, conventionally defined phases of matter. Beyond phase-diagram exploration, we connect the infinitesimal limit of the inferred divergences to the Fisher information metric and analyse its finite-size scaling. This yields critical exponents of the discovered transitions and enables snapshot-based analysis of universality classes [7]. We apply distance learning to a diverse set of systems characterised by conventional local order parameters, non-local topological order, and higher-order correlations. In all cases, we correctly recover boundaries between distinct correlation regimes and, where applicable, quantitatively match established critical behaviour. Finally, we show that distances to suitably chosen reference snapshot distributions help identify the dominant correlations within the discovered clusters, positioning distance learning as a versatile information-geometric probe of quantum many-body physics.

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The dynamical equilibrium of photon BEC in semiconductor VCSELs

Aleksandra Bojakowska [1], Leon Mixa [2], Marcin Gębski [3], James A. Lott [4], Tomasz Czyszanowski [3], Jean-Jacques Greffet [5], Axel Pelster [2], and Maciej Pieczarka [1]

[1] *Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Physics Department and Research Center OPTIMAS, Rhineland-Palatinate Technical University Kaiserslautern-Landau, 67663 Kaiserslautern, Germany*
[3] *Photonics Group, Institute of Physics, Lodz University of Technology, ul. Wolczanska 219,93-005 Łódź, Poland*
[4] *Institute for Solid State Physics, Technical University Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*
[5] *Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry Palaiseau 91127, France*

Photon Bose-Einstein condensates (BECs) have recently been realized in a semiconductor platform in an open cavity [1] and vertical-cavity surface-emitting lasers (VCSELs) [2]. It became immediately clear that the physics of photon BEC in VCSELs are different from those validated in dye-filled microcavity systems. The temperature of the photon gas is measured to be different from the device's temperature and changes as a function of pumping current through the device. These results suggest that crystal lattice, electron-hole active reservoir, and photons are not in thermal equilibrium. The photon temperature is colder than the phonon reservoir for small drive but reaches room temperature near the condensation threshold at higher currents.

To understand the thermodynamics of light thermalization in these systems, we are inspired by two-temperature models of electron relaxation in metals and semiconductors. The steady state in the VCSEL devices is modeled by compensating the energy loss of photons leaving the cavity by the energy flow from the crystal lattice and semiconductor drive to the electron-hole subsystem coupled to the photons. We derive the underlying self-consistent equations from a microscopic theory, which describe the effective cooling of the photon gas in the dynamical equilibrium.

Our developed model for the energy flow is compared to new measurements on our VCSEL devices. To this end, we developed a technique to determine the transparency threshold of the VCSEL's active medium during the measurement. The threshold coincides with the pumping currents corresponding to the BEC transition. The improved experiment also took into account the polarization of the emitted light, and allowed for extracting accurately the temperature of the photon gas under a wide range of currents.

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Harnessing ultracold molecules for quantum simulation

Jonathan M. Mortlock[1] , Adarsh P. Raghuram[1], Francesca M. Blondell[1], Benjamin P. Maddox[1], Rob L. Mellor[1], Lena S. Klar[2], Phillip D. Gregory[1], Simon L. Cornish[1]

1 Department of Physics, Durham University, South Road, Durham, DH1 3LE UK

2 Institut für Quantenoptik, Leibniz Universität Hannover, 30167 Hannover, Germany

Ultracold polar molecules possess a rich internal structure of rotational and hyperfine levels, providing a large Hilbert space whose states can be coherently manipulated to encode and process quantum information. When molecules are brought together, electric dipole-dipole interactions couple these internal states between different molecules, enabling the realisation of entangling gates and correlated many-body phases. Combined with the high level of experimental control now achievable in ultracold gases, this makes polar molecules a compelling platform for quantum simulation

Here, I will report on recent progress with ultracold RbCs molecules as a platform for quantum simulation. These gases are formed via association of ultracold Rb and Cs, and then detected via controlled dissociation imaging of the atoms. Recently, we have developed a dual species quantum gas microscope technique which enables spin-resolved detection of molecules in an optical lattice [1]. I will also discuss how magic-wavelength trapping in RbCs enables long-lived coherent superpositions of rotational states [2]. This has allowed us to demonstrate a synthetic dimension encoded in up to eight coherently coupled levels [3]. We are now working towards experiments using dipolar interactions to study many-body physics in t-J spin models with access to site resolved correlations.

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Dynamics of dipolar quantum droplets at BEC-quantum droplet crossover

Denis Mujo[1], Ivana Vasić[1], Milan Radonjić[2,1] and Axel Pelster[3]

[1]Center for the Study of Complex Systems, Institute of Physics Belgrade, University of Belgrade, Serbia
[2]I. Institute of Theoretical Physics, University of Hamburg, Germany
[3]Physics Department, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Germany

Since the first realization of quantum droplets [1], various experiments have indicated that quantum droplets in a dipolar Bose system are stabilized due to quantum fluctuations [2,3], correcting the ground-state energy. Here we study the dynamics of trapped dipolar droplets using both time-dependent variational methods and full three-dimensional simulations of the extended Gross-Pitaevskii equation. Our focus is on the crossover region between a BEC and a quantum droplet, where the system becomes highly sensitive to parameter variations such as changes of the s-wave scattering length or the strength of the trapping confinement. We identify the critical conditions required to maintain droplet stability when these parameters are varied, including the effects of different variation rates and a complete removal of the trapping potential. In addition, we examine the behavior of collective excitation modes in the vicinity of the BEC-quantum droplet crossover.

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Synchronization of Quasi-Particle Excitations in a Quantum Gas with Cavity-Mediated Interactions

Gabriele Natale, Alexander Baumgärtner, Justyna Stefaniak, David Baur, Simon Hertlein, Dalila Rivero, Tilman Esslinger, Tobias Donner

Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, Otto-Stern-Weg 1, CH-8093 Zurich, Switzerland

Driven-dissipative quantum systems can exhibit collective dynamical phases that are absent in closed systems [1]. The excitation spectrum provides a direct probe of the microscopic mechanisms underlying such transitions, as it reveals how collective modes soften, hybridize, or become unstable. Here, we investigate the phase transition to a dynamical phases using a Bose–Einstein condensate of ^{87}Rb atoms coupled to a high-finesse optical cavity and driven by a transverse pump laser. In this platform, the cavity field mediates long-range interactions between the atoms, while photon loss provides a controlled source of dissipation [2].

Using cavity-assisted Bragg spectroscopy [3], we probe the collective excitation spectrum close to a dynamical instability and resolve two roton-like quasiparticle modes. In this regime, we observe dissipation-induced synchronization at the quasiparticle level, where the two modes coalesce at an exceptional point [4,5]. These results show that synchronization can emerge directly in the elementary excitations of an open many-body system and precede the onset of a dynamical phase [6].

In a complementary direction, we are extending the same platform towards range-tunable cavity-mediated interactions. By replacing the usual global transverse pump with a local scanning pump, we aim to paint the atom–cavity coupling in space and access interactions with controllable spatial range. This approach would broaden the class of effective many-body Hamiltonians accessible in cavity-coupled quantum gases.

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Bose-Einstein Condensates in a Synthetic Magnetic Field with Tunable Orientation

Fengtao Pang1,4, Huaxin He1, 2, Yongping Zhang1* and Chunlei Qu3*

1 Institute for Quantum Science and Technology, Department of Physics, Shanghai University, Shanghai 200444, China

2 Provincial Key Laboratory of Multimodal Perceiving and Intelligent Systems, Jiaxing University, Jiaxing, 314001, China

3 Center for Quantum Science and Engineering, Stevens Institute of Technology, Hoboken, NJ 07030, USA

4 Departament de Fisica, Universitat Autonoma de Barcelona, E-08193 Bellaterra, Spain

We systematically investigate the ground state and dynamics of spinor Bose-Einstein condensates subject to a position-dependent detuning. This detuning induces three related quantities (a synthetic magnetic field, an angular velocity, and an angular momentum), which, due to trap anisotropy, may point in different directions. When the dipole frequencies along the three symmetric axes of the harmonic trap are degenerate, the dipole motion can decompose into two coupled transverse modes in the plane perpendicular to the synthetic magnetic field, and another decoupled longitudinal mode, enabling controllable Foucault-like precession or biconical trajectories depending on the excitation protocol. Furthermore, quenching the orientation of the synthetic magnetic field excites multiple coupled quadrupole modes. We develop a hydrodynamic theory whose predictions match well with Gross-Pitaevskii simulations. This study contributes to a deeper understanding of the effects of the synthetic magnetic field and the excitations of the collective mode in quantum fluids, providing a foundation for future developments in quantum simulation and high-precision sensing technologies.

Fate of the Fermi Surface Coupled to a Single-Wave-Vector Cavity Mode

B. Frank[1], M. Pini[2,3], J. Lang[4], F. Piazza[2,3]

[1]*Institut für Theoretische Physik and Würzburg-Dresden Cluster of Excellence ct.qmat, Technische Universität Dresden, Dresden, Germany*
[2]*Institute of Physics, Augsburg University, Augsburg, Germany*
[3]*Max Planck Institute for the Physics of Complex Systems, Dresden, Germany*
[4]*Institut für Theoretische Physik, Universität zu Köln, Cologne, Germany*

The electromagnetic field of standing-wave or ring cavities induces a spatially modulated, infinite-range interaction between atoms in an ultracold Fermi gas, with a single wavelength comparable to the Fermi length. This interaction has no analog in other systems of itinerant particles and has so far been studied only in the regime where it is attractive at zero distance. Here, we fully solve the problem of competing instabilities of the Fermi surface induced by single-wavelength interactions. We find that while the density-wave (superradiant) instability dominates on the attractive side, it is absent for repulsive interactions, where the competition is instead won by nonsuperradiant superfluid phases at low temperatures, with fermion pairs forming at both vanishing and finite center-of-mass momentum. Moreover, even in the absence of such symmetry-breaking instabilities, the Fermi surface exhibits a peculiar anisotropic deformation. We estimate this full phenomenology to be within reach of dedicated state-of-the-art experimental setups.

Metastability in Interacting Light–Matter Systems: From Photon BEC to Dicke Superradiance

Sayak Ray

Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany
Fachbereich Physik, RPTU Kaiserslautern-Landau, Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany

E-mail: sayak@uni-bonn.de

Over the past decade, composite interacting light-matter systems have emerged as versatile platforms for exploring nonequilibrium phenomena in condensed matter physics. Owing to their driven-dissipative nature, these hybrid systems are subject to both atomic and photonic fluctuations, giving rise to rich dynamical behavior, including the emergence of metastable states. A metastable state is dynamically stable yet distinct from the thermodynamic ground state, and is therefore intrinsically nonequilibrium. This phenomenon is fundamentally different from prethermalization, where long-lived states arise due to approximate conservation laws rather than dynamical stabilization. In this talk, I will present two concrete examples, namely, an open photon Bose-Einstein condensate and nonequilibrium superradiant dynamics in dissipative Dicke model. In these systems, metastable states can emerge in both atomic and photonic degrees of freedom through different mechanisms of dynamical stabilization.

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Neutral atom quantum computation and simulation using EIT based multi-qubit gates

Sinchan Snigdha Rej[1] and Bimalendu Deb[1]

[1] *School of Physical Sciences, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700032, India*

Abstract

Multi-qubit quantum gates are key resources for quantum computation (QC) and digital quantum simulation (DQS). We present a unified framework for realizing high-fidelity multi-qubit gates in neutral atom arrays using Rydberg blockade, Rydberg antiblockade, dark-state dynamics, and geometric phase control. First, we propose schemes for the Toffoli and generalized C^nNOT gates in linear and two-dimensional architectures, respectively, achieving fidelities above 99%, under realistic conditions, with robustness against Doppler-induced dephasing maintaining fidelities beyond 98.5% [1]. We further introduce adiabatic geometric phase gates based on a double STIRAP process, which suppress dynamical phase errors and remain resilient to fluctuations in Rabi frequencies, finite blockade strength, and atomic position disorder, yielding fidelities of 98%–99% for gate times around 0.6 μs [2]. In addition, we propose a multi-qubit Rydberg parity gate (RPG) that reduces circuit depth and enhances noise resilience compared to CNOT-based implementations [3]. Applications to Grover's search algorithm, the Deutsch–Jozsa algorithm, and spin-model simulations demonstrate scalable and experimentally feasible pathways toward fault-tolerant neutral-atom quantum computing.

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Thermal amplification and melting of phases in spin–orbit-coupled spin-1 Bose–Einstein condensates

Ritu[1*], Rajat[1,2], Arko Roy[3], Sandeep Gautam[1]

[1]Department of Physics, Indian Institute of Technology Ropar, Rupnagar 140001, Punjab, India,
[2]Department of Physics, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel,
[3]School of Physical Sciences, Indian Institute of Technology Mandi, Mandi, Himachal Pradesh 175075, India
*ritu.22phz0002@iitrpr.ac.in

We implement Hartree-Fock-Bogoliubov theory with Popov approximation for a homogeneous Raman-induced spin-orbit-coupled spin-1 Bose-Einstein condensate and investigate the effects of finite temperature (T) on the ground-state phase diagram. At zero temperature, SO-coupled spin-1 BEC exhibits three different phases: stripe (ST), plane-wave (PW), and zero-momentum (ZM). We determined the boundaries of ST-PW and PW-ZM phases at finite temperatures. To achieve this, we used coupled Gross-Pitaevskii equations (GPEs) to calculate the condensate wave function and the Bogoliubov-de-Gennes (BdG) equations to compute the dispersion and thermal density. The PW phase dispersion features a rotonic structure with a gap, known as the roton gap. The ST-PW and ST-ZM boundary occurs when the roton gap closes. We calculate the roton gap as a function of Raman coupling (Ω) or quadratic Zeeman field strength (ϵ) to extract the critical points separating the ST phase from the PW or ZM phase at finite temperatures. The PW phase has a finite condensate momentum and the ZM phase has zero momentum. The PW-ZM boundary was determined by the point at which the condensate momentum drops to zero. We present a few representative finite-temperature phase diagrams for the system in the $T-\Omega$ and $T-\epsilon$ planes. Our observations indicate that the ST phase melts at finite temperatures. We also discuss the contrasting roles of quantum and thermal fluctuations in shifting the phase boundary separating the supersolid ST from the PW phase.

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Beyond Kibble-Zurek Scaling in Quenched Binary Bose Superfluids

Subhadeep Patra [1], Arko Roy [1], Seong-Ho Shinn[2], Adolfo del Campo[2,3], Mithun Thudiyangal[4]

[1] *School of Physical Sciences, Indian Institute of Technology Mandi, Mandi-175005 (H.P.), India*
[2] *Department of Physics and Materials Science, University of Luxembourg, L-1511 Luxembourg, Luxembourg*
[3] *Donostia International Physics Center, E-20018 San Sebastian, Spain*
[4] *Center for Quantum Technologies and Complex Systems (CQTCS), Christ University, Bengaluru, Karnataka 560029, India*

We investigate how a gradual increase of the chemical potential drives a two-dimensional binary Bose gas from vacuum into a finite-density condensed state, leading to either a mixed (miscible) or phase-separated (immiscible) configuration depending on the interaction strengths. In the immiscible regime, spontaneous domain formation occurs, and the number of domains, their total boundary length, and their characteristic size at equilibration obey universal Kibble–Zurek (KZ) scaling with the cooling rate. These domain patterns subsequently evolve in a self-similar manner while preserving the KZ scaling laws. In the miscible regime, phase separation is absent; instead, vortices are nucleated and their density follows the same KZ scaling. The spatial statistics of both domains and vortices are well described by a Poisson point process with a density set by the KZ mechanism [1]. These results reveal robust, universal features of far-from-equilibrium condensation dynamics in binary superfluids, with direct relevance for nonequilibrium dynamics in degenerate quantum gases.

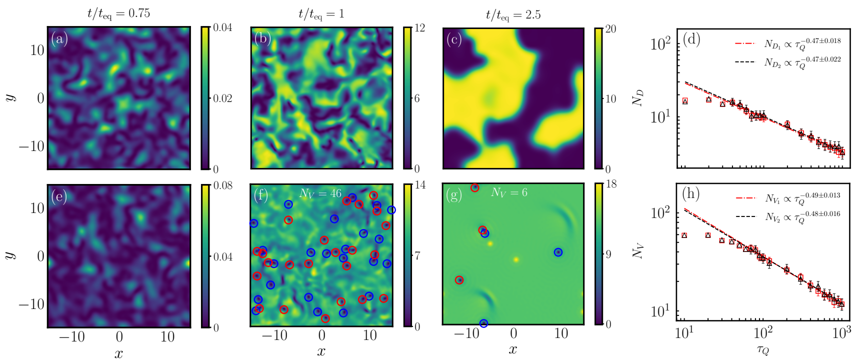

Figure 1: Condensate density evolution $|\psi_1|^2$ for quench time $\tau_Q = 50$. Panels (a)–(c) show domain formation and evolution in the immiscible phase; (e)–(g) show vortex formation in the miscible phase. Panel (d) shows the domain number N_D as a function of τ_Q on a log scale, revealing KZM-like scaling: $N_D \sim \tau_Q^{-\frac{2\nu}{1+z\nu}} = \tau_Q^{-1/2}$, with fitted exponents $N_{D1} \propto \tau_Q^{-0.48\pm0.017}$, $N_{D2} \propto \tau_Q^{-0.49\pm0.024}$. Panels (e)–(g) highlight vortex core formation, with blue/red dots indicating positive/negative winding numbers. Panel (h) shows vortex number scaling: $N_V \sim \tau_Q^{-\frac{2\nu}{1+z\nu}} = \tau_Q^{-1/2}$, with fitted exponents $N_{V1} \propto \tau_Q^{-0.48\pm0.019}$, $N_{V2} \propto \tau_Q^{-0.47\pm0.014}$.

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Unambiguous quantum state discrimination in a PT-symmetric system of a single trapped ion

Chenhao Zhu,[1,#] Tingting Shi,[2,1,#] Liangyu Ding,[2] Zhiyue Zheng,[2] Xiang Zhang,[1,2,*] and Wei Zhang[1,2,*]

[1] *School of Physics and Key Laboratory of Quantum State Construction and Manipulation (Ministry of Education), Renmin University of China, Beijing 100872, China*

[2] *Beijing Academy of Quantum Information Sciences, Beijing 100093, China*

E-mail: shitt97@baqis.ac.cn

Quantum state discrimination (QSD) is of great importance in a wide range of applications of quantum computation and communication [1-2]. It is proposed that with the help of a PT-symmetric Hamiltonian one can orthogonalize two non-orthogonal quantum states and discriminate them unambiguously at the cost of a null probability [3]. We experimentally demonstrate an unambiguous quantum state discrimination of two qubit states under a non-Hermitian Hamiltonian with parity-time-reversal (PT) symmetry in a single trapped $^{40}Ca^+$ ion. [4] We show that any two non-orthogonal states can become orthogonal subjected to time evolution of a PT-symmetric Hamiltonian in both the PT-symmetry preserving and broken regimes, thus can be discriminated unambiguously. For a given pair of candidate states, we show that the parameters of the Hamiltonian must be confined in a proper range, within which there exists an optimal choice to realize quantum brachistochrone for the fastest orthogonalization. Besides, we provide a clear geometric picture and some analytic results to understand the main conclusions. Our work shows a promising application of non-Hermitian physics in quantum information processing.

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Weakly interacting Bose gases in the canonical ensemble

J. Santos[1], A. Pelster[2] and A. Gammal[1]

[1] *Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[2] *Physics Department and Research Center OPTIMAS, RPTU Germany*

Based on the canonical description of a non-interacting Bose gas [1] we work out how both thermodynamic and statistical properties change perturbatively with respect to weak two-particle interactions. Up to first order we obtain a recursion formula for the canonical partition function, which consists of the same Feynman diagrams as the grand-canonical description [2] but with different Feynman rules. Resumming this recursion formula for the canonical partition function allows then to characterize the statistics of the ground-state occupancy by its respective cumulants. We demonstrate the applicability of this approach by analyzing a dilute Bose gas with contact interaction in a box trap. And we compare the results obtained by both periodic and Dirichlet boundary conditions in view of their relevance for current experiments with atomic gases, where the box trap is implemented, for instance, with digital mirror devices.

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Investigating Non-Adiabatic Performance in a BEC Quantum Otto Engine

M. T. Strøe[1], A. M. Morgen[1], S. S. Balling[1], H. Harper-Gardner[2], N. Proukakis[2], and J. J. Arlt[1]

[1] *Center for Complex Quantum Systems, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*
[2] *School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne NE1 7RU*

Quantum heat engines employing BECs as working fluids provide an exciting platform for exploring quantum thermodynamics and many-body quantum physics. Recent theoretical work on the quantum Otto cycle, shows that, for short time scales, efficiency and power oscillates with cycle time [1]. Such oscillations demonstrate that the coherent phase dynamics of the BEC can lead to performance that exceeds that of the classical Otto engine.
Based on previous work [2], we have implemented a quantum Otto cycle in a 39K BEC with tuneable interaction strength and trapping frequencies. In such a system, the strokes of an Otto cycle can be realized by changing the trap frequencies and scattering length within the ensemble. We tried performed such a cycle with a two-to-one compression ratio, and a ten-to-one ratio in the scattering length. This resulted in an engine that demonstrated power oscillations, but did not jet show the enhanced performance. This lack of enhanced performance is likely due to a lag of the magnetic field, which prevents non-adiabatic control of the scattering length.
Current efforts focus on developing a more robust ramping protocol that provides full and independent control of the scattering-length strokes, enabling a more stringent investigation of the predicted quantum effects.

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Interplay of Noise and Reservoir-induced Decoherence in Persistent Currents

Samudra Sur[1], and Thierry Giamarchi[1]

[1] Department of Quantum Matter Physics, University of Geneva, Quai Ernest-Ansermet 24, 1211 Geneva, Switzerland

Persistent current is a hallmark of quantum phase coherence. We study the fate of the persistent current in a non-equilibrium setting[1], where a tight-binding ring is subjected to stochastic disorder as well as a fermionic reservoir attached to each site. We evaluate the current using Keldysh technique and find that it exhibits non-monotonic behavior, suggesting two distinct mechanisms of decoherence. While coupling to the reservoirs introduces a coherence length scale given by the inverse of the coupling strength, the other mechanism is more subtle and driven by the ratio of noise strength to reservoir coupling. The interplay of noise and reservoir constitutes a purely non-equilibrium steady state with a flatter distribution function that we effectively describe using classical rate equations. We discuss possibilities of realizing our findings in ultracold-atom experiments.

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Estimating universal parameters of 1D anyons via Bogoliubov theory

Bin-Han Tang[1], Axel Pelster[2], and Martin Bonkhoff[3]

[1]University of Trento, Trento, Italy; [2]RPTU Kaiserslautern-Landau, Kaiserslautern-Landau, Germany; [3]University of Hamburg, Hamburg, Germany

Recently, the one-dimensional anyon-Hubbard model was realized in a seminal experiment with Cs-atoms [1]. This allowed to confirm previous theoretical predictions that the quasi-momentum distribution is asymmetric for intermediate statistical angles, reflecting inherent spatio-temporal asymmetry. In one-dimensional systems of infinite extent, Bose-Einstein condensation is precluded by strong quantum fluctuations, and the Luttinger paradigm is the governing principle instead. However, for non-integrable models the coupling constants of the theory are only known analytically in the weak-coupling limit, and have to be deduced numerically or with approximate methods in general. To this end, we use a thermodynamic description via a Landau potential, which has to be extremal with respect to both the density and the wave vector characterizing the effective condensate in [1]. The latter induces a current-density coupling as an additional response coefficient, apart from the ordinary density stiffness and phase stiffness. Imposing thermodynamic stability then implies different sound velocities for the propagation to the left or the right. And we compare the stiffnesses with the predictions of Luttinger liquid theory for the anyon-Hubbard model in the dilute limit, where we can slightly extend to higher filling fractions [2].

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Rydberg Physics of Optically Trapped Erbium Atoms

A. Tashchilina 12, D. S. Grün 12, R. Donofrio 12, M. Iaushev 12, M. J. Mark 12, F. Ferlaino 12

1 Universität Innsbruck, Institut für Experimentalphysik, Technikerstraße 25, 6020 Innsbruck, Austria
2 Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria

Laser-cooled neutral atoms in optical tweezers are rapidly emerging as a scalable platform for quantum computing. Alkaline-earth metals and lanthanides offer unique advantages for atomic manipulation due to their rich electronic spectra, opening new possibilities in quantum science. In particular, erbium provides a wide range of optical transitions for cooling, control, and diagnostics. Leveraging this spectral richness, we have devised a scheme for efficient single-atom preparation [1] and ultrafast, number-resolved imaging [2]. The range of opportunities expands further when accessing Rydberg states. Following the first demonstration of Rydberg spectroscopy in erbium [3], we pursued dedicated studies to identify optimal Rydberg levels for quantum gate implementations. We observed a strong atomic polarizability of the Rydberg-excited state and demonstrated trappability in a red-detuned optical tweezer for n as low as 13. Finally, we achieved coherent Rabi oscillations to Rydberg states, marking a crucial first step toward realizing two-atom entanglement with erbium atoms.

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Conserved quantities enable the quantum Mpemba effect in weakly open systems

I. Ulčakar[1,2], G. Lagnese[1], R. Sharipov[2] and Z. Lenarčič[1]

[1] *Jozef Stefan Institute, Ljubljana, Slovenia*
[2] *Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia*

Observation of the quantum Mpemba effect has spurred much interest in its enabling conditions and its relation to the classical counterpart. Here, we consider weakly open many-body quantum systems initialized in different thermal states and examine when the initially farther state relaxes to the (non-equilibrium) steady state faster. We claim that the number of conserved quantities in the unitary part plays a crucial role: the Mpemba effect is possible only when the Hamiltonian commutes with other extensive operators or is integrable. The reason lies in the dynamical evolution happening in spaces of different dimensions. When energy is the only approximately conserved quantity, dissipation pushes the dynamics within a single-parameter manifold of different thermal states. In contrast, for Hamiltonians with several conserved quantities, the dynamics drift in the multi-dimensional space of generalized Gibbs ensembles, whose distance to the steady state is less trivial. We provide numerical results for large system sizes using tensor networks and free-fermion techniques, thereby supporting our claim.

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Control of single spin-flips in a Rydberg atomic fractal

R. C. Verstraten 1*, I. H. A. Knottnerus 2,3,4*, Y. C. Tseng 2,3, A. Urech 2,3, T. S. do Espirito Santo 1,5, V. Zampronio 1,5,6, F. Schreck 2,3, R. J. C. Spreeuw 2,3, and C. Morais Smith 1

1 Institute for Theoretical Physics, Utrecht University, Princetonplein 5, 3584CC Utrecht, The Netherlands.
2 Van der Waals-Zeeman Institute, Institute of Physics, University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands.
3 QuSoft, Science Park 123, 1098XG Amsterdam, The Netherlands.
4 Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands.
5 Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, Campus Universitário, Lagoa Nova, Natal-RN 59078-970, Brazil.
6 Dipartimento di Fisica e Astronomia, Universitá di Firenze, I-50019, Sesto Fiorentino (FI), Italy.
* These authors contributed equally to this work

Rydberg atoms trapped by optical tweezers have emerged as a versatile platform to emulate lattices with different geometries, in which long-range interacting spins lead to fascinating phenomena, ranging from spin liquids to topological states of matter. Here, we show that when the lattice has a fractal geometry with Hausdorff dimension 1.58, additional surprises appear. The system is described by a transverse-field Ising model with long-range van der Waals interactions in a Sierpinski gasket fractal. We investigate the problem theoretically using exact diagonalization, variational mean field, quantum Monte Carlo, and a graph-based numerical technique, SIM-GRAPH, which we developed. We find that in the quantum regime, the phase diagram exhibits phases in which the spins flip one-by-one. The theoretical results are in excellent agreement with experiments performed with single 88Sr atoms trapped by optical tweezers arranged in a fractal geometry. The magnetization and von Neumann entanglement entropy reveal several regimes in which single spin-flips are delocalized over many sites of one sublattice, thus allowing for an unprecedented control of a cascade of phase transitions in a manybody system. These results expand the possibilities of Rydberg atoms for quantum information processing and may have profound implications in quantum technology.

Reference: ArXiv:2509.03514

Two-Body Contact Dynamics in a Bose Gas near a Fano-Feshbach Resonance

A. Journeaux[1], J. Veschambre[1], M. Lecomte[1], E. Uzan[1], J. Dalibard[1], F. Werner[1], D.S. Petrov[2], R. Lopes[1]

[1]Laboratoire Kastler Brossel, College de France, CNRS, ENS-Université PSL, Sorbonne Universite, 11 Place Marcelin Berthelot, 75005 Paris, France
[2] Université Paris-Saclay, CNRS, LPTMS, 91405, Orsay, France

We investigate the real-time buildup of short-range correlations in a nondegenerate ultracold Bose gas near a narrow Fano-Feshbach resonance. Using rapid optical control, we quench the closed-channel molecular energy to resonance on submicrosecond timescales and track the evolution of the two-body contact through photodissociation losses. Repeated pulse sequences enhance sensitivity to early-time two-body losses and reveal long-lived coherence between atom pairs and molecular states. The observed dynamics are accurately reproduced by our dynamical two-channel zero-range theory, which explicitly accounts for the resonance's narrow width and finite closed-channel decay, establishing a predictive framework for correlation dynamics in quantum gases near Fano-Feshbach resonances.

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Anyonization of bosons: an effective swap model

Botao Wang,[1,2] Amit Vashisht,[1,2] Sudipta Dhar,[3] Milena Horvath,[3] Yi Zeng,[3] Mikhail B. Zvonarev,[4] Manuele Landini,[3] Yanliang Guo,[5,3] Hanns-Christoph Nägerl,[3] and Nathan Goldman[1,2,6]

[1] *Center for Nonlinear Phenomena and Complex Systems, Université Libre de Bruxelles, CP 231, Campus Plaine, 1050 Brussels, Belgium*

[2] *International Solvay Institutes, 1050 Brussels, Belgium*

[3] *Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, Technikerstraße 25, Innsbruck, 6020, Austria*

[4] *Université Paris-Saclay, CNRS, LPTMS, 91405 Orsay, France*

[5] *Key Laboratory of Quantum State Construction and Manipulation (Ministry of Education), School of Physics, Renmin University of China, Beijing 100872, China*

[6] *Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-Université PSL, Sorbonne Université, 11 Place Marcelin Berthelot, 75005 Paris, France*

Anyons emerge as elementary excitations in low-dimensional quantum systems and exhibit behavior distinct from bosons or fermions. Despite intensive theoretical efforts, the experimental realization of anyons in one dimension has proven to be difficult. Here we will present the recent observation of emergent anyonic correlations in a one-dimensional strongly interacting quantum gas, based on the phenomenon of spin-charge separation [1]. A mobile impurity provides the necessary spin degree of freedom to engineer and probe these anyonic correlations. As a novel framework, we propose an effective "swap" model to capture the anyonization mechanism at the microscopic level [2]. The dynamical properties of the anyonic correlations are further explored. Our work provides new avenues for engineering many-body anyonic behavior in quantum simulation platforms.

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Beyond single-atom coupling: self-organization through cavity-induced atom-pair interactions in a Fermi gas

Sankalp Sharma[1], Farokh Mivehvar[2] and Tomasz Wasak[1]

[1]*Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, Grudziądzka 5, 87-100 Toruń, Poland*
[2]*Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*

Engineering strong interactions in fermionic quantum systems through light-matter coupling enables the exploration of novel phases of matter and the creation of highly correlated states with applications in quantum communication, computation, and metrology. While single atom–photon coupling has received considerable attention, the collective excitation of atom pairs by single photons can unlock fundamentally new regimes of correlated many-body dynamics. Here, we develop a theoretical framework to describe fermionic atoms in an optical cavity, where each photon interacts simultaneously with a pair of atoms. This pairwise coupling induces an effective atom-atom interaction mediated by the photon field, which we show can lead to spontaneous breaking of translational invariance and self-ordering of the atomic ensemble. By analyzing the structure of the ordered state as a function of pump and atom-atom interaction strength, we map out a phase diagram, unveiling nontrivial solutions that signal transitions between distinct quantum phases.

Our results demonstrate how cavity-mediated pair interactions in fermionic ensembles can be harnessed to realize and control emergent ordered phases, paving the way for further studies of exotic light-induced phenomena and the development of novel quantum technologies.

Breathing and Fission of Magnetic Multi-solitons

G. Brochier[1], Y. Li[1], S. Wattellier[1], S. Philips[1], F. Rabec[1], S. Nascimbene[1], J. Dalibard[1], J. Beugnon[1,2]

[1]Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-PSL University, Sorbonne Université, 11 Place Marcelin Berthelot, 75005 Paris, France
[2] Institut Universitaire de France (IUF)

We report the deterministic experimental realization and controlled fission of magnetic multi-soliton states in a uniform quasi-one-dimensional immiscible two-component Bose gas. We explore the Manakov regime, where the spin dynamics is well described by the easy-axis Landau-Lifshitz equation (LLE). The gauge equivalence between the easy-axis LLE and the attractive nonlinear Schrödinger equation (NLSE) enables the direct construction of magnetic multi-solitons from the well-known NLSE solutions. We observe the two- and three- soliton states, which exhibit robust breathing in quantitative agreement with integrable theory. By introducing a weak, localized perturbation, we controllably break integrability and induce the splitting of a two-soliton into its fundamental constituents [1]. This process reveals the composite structure of multi-soliton states and realizes an experimental analog of the inverse scattering transform. [2]

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Revealing the structure of the heavy Fermi polaron

M. Rautenberg[1], T. Krom[1], E. Lippi[1], E. Dizer[2], O. Bleu[2], R. Schmidt[2], T. Enss[2], L. Chomaz[1], M. Weidemüller[1]

[1] *Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany*
[2] *Institut für Theoretische Physik, Universität Heidelberg, Heidelberg, Germany*

We present spectroscopic measurements probing the structure and dynamics of the heavy Fermi polaron. In our experiment, this system is realized by heavy cesium (^{133}Cs) impurities immersed in a deeply degenerate Fermi gas of much lighter lithium (^{6}Li) atoms.

Fermi polarons—quasiparticles formed by impurities dressed by excitations of a surrounding Fermi sea—have been extensively studied both theoretically and experimentally. The large mass imbalance in the Li–Cs system enables access to the regime of heavy impurities, where conventional quasiparticle descriptions are expected to break down. In the limit of an infinitely heavy impurity, Landau's quasiparticle picture [1] ceases to apply and the system is instead described by a state that in the thermodynamic limit is orthogonal to the Fermi sea in the absence of the impurity, a phenomenon known as the Anderson orthogonality catastrophe (AOC) [2].

By tuning the impurity–bath interaction near a magnetic Li–Cs Feshbach resonance, we probe both the ground and excited states of the polaron as a function of interaction strength using spectroscopy between two Cs hyperfine states. Comparison with theoretical models provides insight into the effects of finite temperature and finite impurity mass and their relation to the AOC limit.

While these spectra are described by the linear-response regime, we can also continuously drive the impurities between interacting and non-interacting states. For a weak drive, the reduction of the Rabi frequency of the interacting system with respect to the bare Cs Rabi frequency can be attributed to the quasi-particle weight in a Chevy-type picture [3]. On the other hand, a non-trivial dependence of this reduction as a function of the driving strength has been derived for an infinitely heavy impurity governed by the AOC [4]. However, a theoretical description covering the full range of driving strengths—from weak driving to the regime where the drive exceeds the Fermi energy—remains an open challenge for heavy Fermi polarons at finite temperature.

Together with time-domain spectroscopy (Ramsey and spin-echo protocols) probing the dynamical formation of the polaron, our measurements provide a comprehensive characterization of the Fermi polaron with the largest mass imbalance accessible in alkali mixtures, establishing this system as a versatile platform for testing quantum many-body theories of impurities in degenerate Fermi gases.

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Mach-Zehnder interferometer for in-situ characterization of atom traps

A. Wolf[1,2] and M. A. Efremov[1,2]

[1]*German Aerospace Center (DLR), Institute of Quantum Technologies, 89081 Ulm, Germany*

[2]*Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, 89069 Ulm, Germany*

Controlling dynamics of cold atoms in traps is a key tool for most fundamental studies and numerous realizations of quantum simulators and quantum sensors. They require accurate modeling and characterization of the underlying trapping potentials. We introduce a technique based on the Mach-Zehnder interferometer for in-situ characterization of weakly anharmonic potentials. By simulating the interferometer in an optical dipole trap, we can accurately determine its trap frequency and upper bounds onto anharmonicity magnitudes.

Microscopy of Light-induced Collective Behaviour in Strongly Interacting Fermi Gases

Zeyang Xue[1], Gaia Bolognini[1], Kyuhwan Lee[1], Aurélien Fabre[1], Janica Böhler[1], Tabea Bühler[1], Timo Zwettler[1], Giulia D. Pace[1], Victor Helson[1] and Jean-Philippe Brantut[1]

[1] Institute of Physics and Center for Quantum Science and Engineering, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

We study quantum many-body phenomena of strongly correlated fermions using Lithium 6 atoms cooled to the degenerate regime and a high-finesse optical cavity. The atoms inside the cavity combine the short-range contact interaction between atoms with the cavity-mediated long-range interaction induced by photon exchange. This configuration features a phase transition to a density-wave ordered state. This poster reports the first in-situ observation of density-wave ordering. The local density-wave information is extracted by a high-resolution microscope with a numerical aperture of 0.39. We obtain direct information about the phase transition order parameter by quantifying the density-wave modulation contrast. We further investigate the correlation between atomic and photonic signatures of the density-wave ordering phase transition by recording the amplitude and phase of the photonic signal through heterodyne detection. We foresee several research directions made possible by the high-resolution microscope. Phase-contrast imaging will enable in-situ access to local magnetization, allowing us to investigate the interplay between spin pairing and density-wave ordering. By integrating a digital micromirror device into the imaging path, the microscope also provides programmable optical control over the external potential, enabling studies of degenerate fermions confined in a uniform 2D box trap. Finally, by driving the atoms with multiple pump frequencies, we extend the light-matter interaction into the multimode cavity regime, where the coexistence and competition of several cavity-mediated interactions are expected to give rise to multiple symmetry-broken states and a richer phase diagram.

Effects of long-range hopping on the stability of current-carrying Bose-condensed states in a hard-core Bose-Hubbard model

Yoshihiro Yabuuchi[1,2,3], Ippei Danshita[2]

[1]*Department of Physics, Osaka Metropolitan University, Osaka, Japan*

[2]*Department of Physics, Kindai University, Osaka, Japan*

[3] *Institute for theoretical physics III , University of Stuttgart, Stuttgart, Germany*

Recent advances in Rydberg atom arrays [1] and trapped-ion systems [2] have enabled the realization of quantum many-body systems described by the spin-1/2 XY model with long-range spin-exchange couplings whose strength decays algebraically as $r^{-\alpha}$, where r is the distance between sites and α is the decay exponent. Through the well-established spin-boson mapping from the spin-1/2 XY model to the hard-core Bose-Hubbard model [3], this long-range spin exchange corresponds to long-range hopping of hard-core bosons with the same algebraic decay.

We theoretically study how long-range hopping affects the stability of current-carrying condensed states of hard-core bosons within a mean-field framework [4].

We find that, as α decreases from a large value, the critical quasi-momenta for Landau and dynamical instabilities decrease and eventually vanish at $\alpha = 3$. This result indicates that long-range hopping suppresses the stability of current-carrying Bose-condensed states. Furthermore, near $\alpha = 3$, we find that the critical quasi-momentum associated with the dynamical instability obeys the scaling form $\propto \Delta^{1+\Delta}$, where $\Delta = \alpha - 3$. Thus, the scaling exponent itself depends on Δ, in contrast to typical critical behavior in short-range systems, where the critical exponent takes a constant value. The emergence of such an unusual scaling law highlights a remarkable consequence of the long-range nature of hopping.

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Dual-species Rydberg arrays for quantum information processing and quantum simulation

Peng Yin[1,2], Marvin Scholz[1,2], Jana L. Bonet Fernández[1,2], and Hannes Bernien[1,2,3]

[1] *Institute for Quantum Optics and Quantum Information, 6020 Innsbruck, Austria*
[2] *Institute for Experimental Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[3] *Pritzker School of Molecular Engineering, University of Chicago, IL 60637, USA*

Neutral atom arrays represent a versatile platform for quantum information processing and simulation. However, implementing mid-circuit operations—such as site-selective readout and single-qubit addressing—remains a significant challenge in single-species arrays, despite their necessity for quantum error correction. Dual-species Rydberg arrays, incorporating distinct atomic species (e.g., Rb-87 and Cs-133), offer a compelling solution with negligible crosstalk and tunable inter- and intra-species interaction[1-3]. Building upon our previous demonstrations of mid-circuit readout[2], tunable inter-species Rydberg interactions[3], and quantum cellular automata[4], our next-generation dual-species platform aims to: (1) enhance two-qubit gate fidelities through optimized Rydberg state selection and pulse shaping; (2) develop novel quantum protocols by leveraging the high tunability of inter- and intra-species interactions; (3) simulate complex many-body models characterized by tunable asymmetric interactions; and (4) implement continuous noise sensing using interleaved Rb and Cs qubit arrays. These advancements will significantly expand the frontiers of dual-species Rydberg array platforms for scalable quantum computation, many-body simulation, and quantum metrology.

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Realizing Unitary k-designs with a Single Quench

Yi-Neng Zhou*[1], Robin Löwenberg[1], and Julian Sonner[1]

[1]Department of Theoretical Physics, University of Geneva, 24 quai Ernest-Ansermet, 1211 Genève 4, Suisse

Abstract

We present a single-quench protocol that generates unitary k-designs with minimal control. A system first evolves under a random Hamiltonian H_1; at a switch time $t_s \geq t_{\mathrm{Th}}$ (the Thouless time), it is quenched to an independently drawn H_2 from the same ensemble and then evolves under H_2. This single quench breaks residual spectral correlations that prevent strictly time-independent chaotic dynamics from forming higher-order designs. The resulting ensemble approaches a unitary k-design using only a single control operation—far simpler than Brownian schemes with continuously randomized couplings or protocols that apply random quenches at short time intervals. Beyond offering a direct route to Haar-like randomness, the protocol yields an operational, measurement-friendly definition of t_{Th} and provides a quantitative diagnostic of chaoticity. It further enables symmetry-resolved and open-system extensions, circuit-level single-quench analogs, and immediate applications to randomized measurements, benchmarking, and tomography.

*Email: zhouyn.physics@gmail.com