Frontiers of Quantum Gas Microscopy

727. WE-Heraeus-Seminar

03 Apr - 08 Apr 2022

Hybrid
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 727. WE-Heraeus-Seminar:

The efficient preparation and characterization of quantum many-body states currently poses one of the biggest challenges in physics, and lies at the interface of quantum computation, quantum simulation and condensed matter physics. In recent years, quantum gas microscopy allowed us to reach an unprecedented level of local control over small-scale entangled systems, yielding programmable systems with full quantum state readout. This led to quantum simulations of a wide class of model Hamiltonians, showing, for instance, strongly correlated phenomena, topology, or dynamics far from equilibrium. The quantum states are currently approaching regimes in which the state complexity challenges numerical techniques, and both computation and reconstruction of the exact quantum states becomes challenging owing to the large Hilbert space dimensions. Characterization of such states requires the development of new observables that are built out of microscopic quantities and make use of the novel capabilities of quantum simulation platforms.

This seminar, which will bring together about 80 participants in April 2022, will provide a comprehensive overview of the different aspects of this rapidly developing field. Leading international experts review the present status of the microscopic control of strongly correlated quantum many-body states, from both the experimental and theoretical point of view, and discuss future trends and perspectives. Participants are invited to present their current research in the poster sessions. In addition, outstanding contributions are selected for contributed talks.

Scientific Organizers:

Prof. Dr. Fabian Grusdt	LMU Munich, Germany E-mail: fabian.grusdt@physik.uni-muenchen.de
Prof. Dr. Julian Léonard	TU Vienna, Austria E-mail: julian.leonard@tuwien.ac.at

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, 3 April 2022

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

Monday, 4 April 2022

07:30 – 08:45	*BREAKFAST*	
08:45 – 09:00	Scientific Organizers	**Welcome and opening**
09:00 – 09:45	Zoe Yan	**Microscopy of quantum correlations in an ultracold molecular gas**
09:45 – 10:30	Corinna Kollath	**Driven or dissipative impurities in fermionic quantum gases**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Tommaso Calarco	**Quantum firmware: optimal control for quantum simulators**
11:45 – 12:15	Annabelle Bohrdt	**A microscopic view on the Fermi-Hubbard model: from artificial intelligence to strong pairing**
12:15	*LUNCH*	

Program

Monday, 4 April 2022

14:00 – 14:45	Eun-Ah Kim (online)	**Machine Learning for Quantum Simulation**
14:45 – 15:30	Immanuel Bloch	**From Polaronic Metals to Hole Pairing - Exploring Fermi-Hubbard Systems using Quantum Gas Microscopy**
15:30 – 16:00	Andrea Bergschneider	**From correlations in a bilayer Hubbard model to polarons in atomically thin semiconductors**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Norman Yao (online)	**A Landau Theory for Spin Squeezing**
17:15 – 18:00	Christian Gross	**The low-temperature challenge in optical lattices**
18:00 – 18:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
18:15	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, with complimentary drinks)*	
20:30 – 21:30	Eugene Demler	**Quantum simulations: from the Fermi Hubbard model to quantum magnetism**

Program

Tuesday, 5 April 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Jens Eisert	**Quantum readout using quantum gas microscopes**
09:45 – 10:30	Giacomo Roati	**Tunneling transport of strongly interacting Fermi gases across the superfluid transition**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Hannes Bernien	**A dual-element atom array**
11:45 – 12:15	Jad Halimeh (online)	**Enhancing disorder-free localization through dynamically emergent local symmetries**
12:15	*LUNCH*	
14:00 – 14:45	Mikhail Lukin (online)	**Exploring quantum matter using programmable atom arrays**
14:45 – 15:30	Cindy Regal (online)	**Time-of-flight quantum tomography of single atom motion in an optical tweezer**
15:30 – 16:00	Daniel González Cuadra	**Co-designed quantum simulation of non-abelian gauge theories with Rydberg qudits**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Adam Kaufmann (online)	**New frontiers in atom arrays and quantum gas microscopes using alkaline-earth atoms**
17:15 – 18:00	**Poster flash**	
18:00	DINNER	
20:30 – 21:30	**Poster session I**	

Program

Wednesday, 6 April 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Markus Oberthaler	**Quantum Field Simulator –Universal Time Dynamics & Relativistic Fields in Ultracold Gases**
09:45 – 10:30	Jörg Schmiedmayer	**Emergent Quantum Simulators**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Jessie Zhang	**Optical tweezer arrays of polar molecules from the bottom-up**
11:45 – 12:15	Waseem Bakr (online)	**New directions with fermionic quantum gas microscopes: non-local interactions and programmable geometries**
12:15	*LUNCH*	
14:00 – 18:00	**Excursion**	
18:00	*DINNER*	
20:30 – 21:30	Antoine Browaeys	**Many-body physics with arrays of Rydberg atoms in resonant interaction**

Program

Thursday, 7 April 2022

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:45	Henning Moritz	**Fermionic superfluids in two and three dimensions**
09:45 – 10:30	Tilmann Esslinger	**Self-oscillating and Floquet-driven quantum pumps**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Selim Jochim	**Emergence of many body physics, atom by atom**
11:45 – 12:15	Luca Asteria	**Microscopy of ultracold atoms in optical lattice via quantum gas magnification**
12:15	*LUNCH*	
14:00 – 14:45	Markus Greiner	**Ultracold Atom Quantum Simulations: From Fermi-Hubbard to Fractional Quantum Hall Physics**
14:45 – 15:30	Nathan Goldman	**Orbital order and chiral currents of interacting bosons with π-flux**
15:30 – 16:00	Torsten Zache	**Entanglement Spectroscopy and probing the Li-Haldane Conjecture in Topological Quantum Matter**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:15	Dries Sels (online)	**Tba**
17:15 – 18:00	Ana Maria Rey (online)	**Observation and control of elastic p-wave interactions between fermions in an optical lattice**
18:00	*DINNER*	
20:30 – 21:30	**Poster session II**	

Posters

Posters P1

Tobias Becker	**Canonically consistent master equation**
Stefan Birnkammer	**Prethermalization in confined spin chains**
Julian Boesl	**Fractional quantum Hall states near the first Mott lobe**
Sandra Buob	**Towards a strontium quantum gas microscope**
Cesar Cabrera Cordova	**Fast long-distance transport of cold cesium atoms**
Eva Casotti	**Towards an erbium-dysprosium quantum gas microscope**
Sayan Choudhury (online)	**Self-ordered Time Crystals: Periodic Temporal Order under Quasiperiodic Driving**
Renan da Silva Souza	**Green's function approach to the Bose-Hubbard model with disorder**
Marco Di Liberto	**Topological phonons in arrays of ultracold dipolar particles**
Luca Donini	**Towards ultracold atoms in a kagome optical lattice with single-site-resolved imaging**
Niklas Euler	**Certification of High-Dimensional Entanglement in Ultracold Atom Systems**
Félix Faisant	**Building a strontium quantum gas microscope to study the Bose-Hubbard out-of-equilibrium dynamics**

Posters P1

Robin Groth	**Combining quantum computation and simulation on a single platform**
Tobias Hammel	**A New Apparatus for High Cycle Rate Experiments using Lithium-6**
Mehedi Hasan	**Observation of Anisotropic Zitterbewegung in Non-Abelian Gauge Field**
Timon Hilker	**The Munich Lithium quantum microscope(s)**
Sarah Hirthe	**Observation of Hole Pairing in Mixed-Dimensional Fermi-Hubbard Ladders**
Krzysztof Jachymski	**Quantum simulation with hybrid ion-atom and Rydberg-atom systems**
Philipp Preiss	**Quantum Information in Assembled Optical Lattice Systems**

Posters P2

Maximilian Kaiser	**Towards fast, deterministic preparation of few-fermion states**
Matjaz Kebric	**Exploring Phase Diagrams of 1D Z2 Lattice Gauge Theory with Dynamical Matter**
Hans Keßler	**Observation of a continuous time crystal**
Nick Klemmer	**Realizing a superlattice for studying topological systems with interacting fermions**
Viacheslav Kuzmin	**Probing infinite many-body quantum systems with finite-size quantum simulators**
Woo Jin Kwon	**Sound Emission and Vortex Annihilation in a Superfluid Vortex Collider**
Hannah Lange	**Adaptive Quantum State Tomography with Active Learning**
Simon Mathias Linsel	**Thermal deconfinement in doped Z2 lattice gauge theories**
Niclas Luick	**Observation of Josephson oscillations and superfluidity in a strongly correlated 2D Fermi gas**
Philipp Lunt	**Mesoscopic Fermion systems in rotating traps**
Natalia Masalaeva	**Spin and density self-ordering in dynamic polarization gradients fields**
Conall Vincent McCabe	**Confinement of Dynamical Charges in Zn Lattice Gauge Theory**

Posters P2

Hamid Md (online)	**Vortices in rotating Bose gas interacting via nite range Gaussian potential in a quasi-two-dimensional harmonic trap**
Nader Mostaan	**Quantized transport of solitons in nonlinear Thouless pumps**
Maximilian Prüfer	**Quantum probes for many-body systems**
Henning Schlömer	**Robust stripes in the mixed dimensional t-J model**
Philipp Stammer	**Generation of massively entangled optical states**
Adamantios Panagiotis Synanidis (online)	**Distinguishing Cavity Induced Transparency from Autler-Townes Splitting using Exceptional Points**
Isaac Tesfaye	**Adiabatic charge pumping in bosonic Chern-insulator analogs**
Fan Yang (online)	**Liouvillian Skin Effect in an Exactly Solvable Model**
Philip Zechmann	**Tunable transport in the mass-imbalanced Fermi-Hubbard model**

Abstracts of Lectures

(in alphabetical order)

Microscopy of ultracold atoms in optical lattice via quantum gas magnification

L. Asteria[12], H. P. Zahn[1], M. N. Kosch[1], V. Singh[34], L. Freystatzky[23], L. Mathey[123], K. Sengstock[123], C. Weitenberg[12]

[1]*Institut für Laserphysik, Hamburg, Germany*
[2] *The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany*
[3] *Zentrum für Optische Quantentechnologien, Hamburg, Germany*
[4] *Institut für Theoretische Physik, Hannover, Germany*

In this contribution we present results on quantum gas magnification as a microscopy tool for ultracold atoms in optical lattices.
We developed a matter wave optics protocol which magnifies the atomic density distribution by almost two orders of magnitude [1], allowing to image the magnified cloud in a single-shot and with sub-lattice resolution by using standard optical imaging techniques. We demonstrated that this approach works with 3D systems with many particles per lattice site, because it does not have the limitations of a small depth of focus and of light induced collisions.

We report on several experiments made possible by this new technique: We show how the temperature of a cold Rubidium cloud in the lattice could be directly obtained from the density distribution. We combined the site-resolved imaging with magnetic resonance techniques for local addressing of individual lattice sites. The sub-lattice resolution is demonstrated by observing the dynamics within the lattice sites after a lattice potential quench.

Finally, we report on a novel phenomenon that occurs in the regime of many particles per lattice site when introducing a strong force into the system [2]. Single-particle tunneling becomes thus an off-resonant process, making the correlated tunneling of pairs of atoms the relevant dynamical process. The effect of this correlated dynamics can be directly seen via quantum gas magnification and manifests itself with the formation of a density wave which spontaneously breaks the symmetry of the lattice. Quantum gas magnification opens the path for spatially resolved studies of new quantum many-body regimes, like e.g. 3D systems, orbital lattices, and lattice geometries with smaller lattice spacing. It could be applied to atomic species, where efficient laser cooling or deep optical traps are not available.

References

[1] L. Asteria, H. P. Zahn, M. N. Kosch, K. Sengstock, C. Weitenberg, Nature **599**, 571-575 (2021)
[2] H. P. Zahn, V. Singh, M. N. Kosch, L. Asteria, L. Freystatzky, L. Mathey, K. Sengstock, C. Weitenberg, arXiv:2108.11917 (Accepted in PRX, 2022)

New directions with fermionic quantum gas microscopes: non-local interactions and programmable geometries

Benjamin Spar[1], Max Pritchard[1], Elmer Guardado-Sanchez[1], Sungjae Chi[1], Zoe Yan[1] and W. Bakr[1]

[1]*Princeton University, Princeton NJ, USA*

I will report on two new experimental directions in studying strongly correlated fermions with quantum gas microscopes: non-local interactions and programmable lattice geometries.

First, I will describe the realization of strong, non-local interactions between the fermions using Rydberg-dressing [1]. We introduce a small admixture of a Rydberg state to the ground state of the atoms in a spin-polarized gas. The resulting off-site interactions allow us to realize a mixed dimensional *t-V* model. We probe the interplay of non-local interactions with tunneling by studying the short-time relaxation dynamics of charge density waves in the gas, finding that strong interactions slow down the relaxation. This work opens the door for quantum simulations of other rich systems with strong non-local interactions including extended Fermi-Hubbard models.

Next, I will discuss our progress towards realizing a programmable fermionic quantum simulator using optical tweezer arrays [2]. A new Floquet technique for creating two-dimensional arrays provides us with a full control over individual tweezer depths and the array geometry. We demonstrate loading low-entropy arrays of various geometries with up to 50 fermions in the ground motional state of the tweezers, spin-resolved detection of individual atoms in the array and preparation of correlated states of the Fermi-Hubbard model. By post-selecting on arrays with perfect filling, this approach may allow reaching much lower entropy systems than realized with optical lattices.

References

[1] E. Guardado-Sanchez *et al.*, Phys. Rev. X 11, 021036 (2021).
[2] B. Spar *et al.*, arxiv:2110.15398 (2021).

From correlations in a bilayer Hubbard model to polarons in atomically thin semiconductors

A. Bergschneider[1], N. Klemmer[1], J. Fleper[1], V. Jonas[1], M. Gall[1], N. Wurz[1], J. Samland[1], C.F. Chan and M. Köhl[1]

and

L. B. Tan[2], T. Smolenski[2], O. Huber[2], F. Colangelo[2], A. Tugen[2], M. Kroner[2] and A. Imamoglu[2]

[1] Physikalisches Institut, University of Bonn, D-53115 Bonn, Germany
[2] Institute for Quantum Electronics, ETH Zürich, CH-8093 Zürich, Switzerland

The interplay between kinetic and interaction energy of fermions in a periodic potential leads to a rich phase diagram. Extending the system by introducing additional coupling strengths leads to additional competing phases. I will present our latest results on interacting fermions in two 2D-lattice arrays that are coupled to a bilayer system [1]. By controlling the ratio of inter- and intralayer coupling, we observed competing magnetic correlations within and across layers.

In the second part of my talk, I will give an introduction into transition-metal dichalcogenides. These atomically thin semiconductors are a novel platform for exploring two-dimensional quantum systems at the intersection of condensed matter and quantum optics. I will present our results on exciton-polarons in such charge-tunable heterostructures [2,3], which we study with spectroscopic and time-resolved methods.

References

[1] M. Gall, et al., Nature **589**, 7840 (2021)
[2] M. Sidler et al., Nature Physics **13**, 255-261 (2017).
[3] L. B. Tan et al., Physical Review X, **10** (2), 021011 (2020).

A dual-element atom array

Hannes Bernien

University of Chicago, USA

Reconfigurable arrays of neutral atoms are an exciting new platform to study quantum many-body phenomena and quantum information protocols. Their excellent coherence combined with programmable Rydberg interactions have led to intriguing observations such as quantum phase transitions, the discovery of quantum many-body scars, and the recent realization of a topological spin liquid phase.

Here, I will introduce new methods for controlling and measuring atom arrays that open up new directions in quantum state control, quantum feedback and many-body physics. First, I will introduce a dual species atomic array in which the second atomic species can be used to measure and control the primary species [1]. This will lead to the possibility of performing quantum nondemolition measurements and new ways of engineering large, entangled states on these arrays. Furthermore, prospects of studying open systems with engineered environments will be discussed.

An alternative, hybrid approach for engineering interactions and scaling these quantum systems is the coupling of atoms to nanophotonic structures in which photons mediate interactions between atoms. Such a system can function as the building block of a large-scale quantum network. In this context, I will present quantum network node architectures that are capable of long-distance entanglement distribution at telecom wavelengths [2].

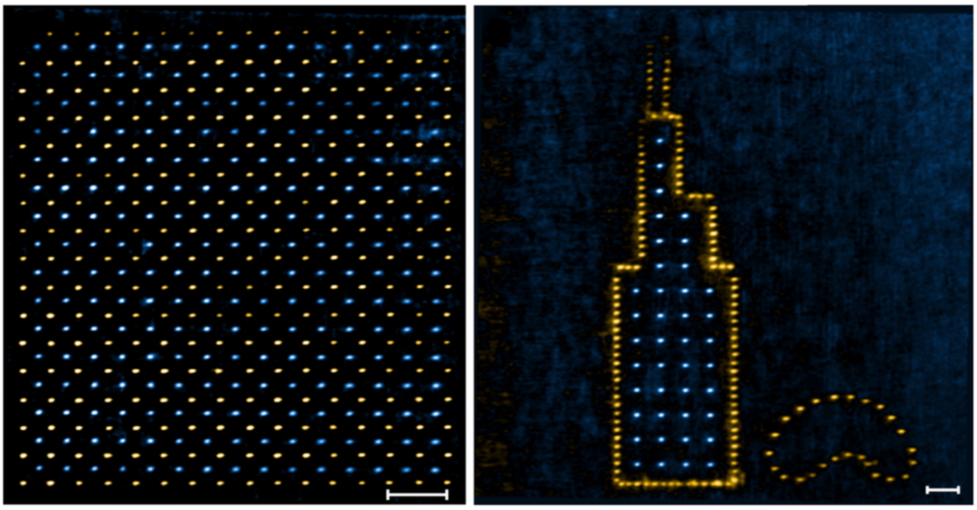

Figure 1: Average fluorescence of a dual-element array of rubidium (blue) and cesium (yellow) atoms. Left: 512 sites of interleaved rubidium and cesium traps. Right: Two Chicago landmarks, demonstrating flexible positioning.

References

[1] K. Singh, S. Anand, A. Pocklington, J.T. Kemp, H. Bernien, PRX **12**, 011040 (2022)

[2] S.G. Menon, K. Singh, J. Borregaard, H. Bernien, NJP **22**, 073033 (2020)

From Polaronic Metals to Hole Pairing - Exploring Fermi-Hubbard Systems using Quantum Gas Microscopy

I. Bloch[1]

[1]Max Planck Institute of Quantum Optics, Garching, Germany
[2] Ludwig Maximilians Universität, Fakultät für Physik, München, Germany

More than 30 years ago, Richard Feynman outlined his vision of a quantum simulator for carrying out complex calculations on physical problems. Today, his dream is a reality in laboratories around the world. This has become possible by using complex experimental setups of thousands of optical elements, which allow atoms to be cooled to Nanokelvin temperatures, where they almost come to rest. Recent experiments with quantum gas microscopes allow for an unprecedented view and control of artificial quantum matter in new parameter regimes and with new probes. In our atomic fermionic quantum gas microscope, we can detect both charge and spin degrees of freedom simultaneously, thereby gaining maximum information on the intricate interplay between the two in the Fermi Hubbard model. In my talk, I will show how we can reveal hidden magnetic order, directly image individual magnetic polarons, probe the fractionalisation of spin and charge in dynamical experiments, reveal the crossover from a polaronic metal to a Fermi liquid when continuously increasing the doping in the system and directly observe hole pairing. For the first time we thereby have access to directly probe microscopic correlation properties of quantum matter and to explore its real space resolved dynamical features also far from equilibrium.

A microscopic view on the Fermi-Hubbard model: from artificial intelligence to strong pairing

A. Bohrdt[1,2], Christie S. Chiu [3], Geoffrey Ji[2], Muqing Xu[2], Daniel Greif[2], Michael Knap[4,5], Joannis Koepsell[5,6], Dominik Bourgund[5,6] , Pimonpan Sompet[5,6] , Sarah Hirthe[5,6] , Yao Wang[7], Guillaume Salomon[8], Christian Gross[9], Cole Miles[10], Ruihan Wu[11], Kilian Q. Weinberger[11] , Eun-Ah Kim[10], Markus Greiner[2], Immanuel Bloch[5,6,12] , Eugene Demler[13], Fabian Grusdt[5,12]

[1]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[2] Department of Physics, Harvard University, Cambridge, MA 02138, USA.
[3] Department of Electrical Engineering, Princeton University, Princeton, NJ, USA
[4] Department of Physics,Technical University of Munich, 85748 Garching, Germany
[5] Munich Center for Quantum Science and Technology (MCQST), München, Germany
[6] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[7] Department of Physics and Astronomy, Clemson University, Clemson, SC 29631, USA
[8] Institut für Laserphysik, Universität and The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[9] Physikalisches Institut, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany
[10] Department of Physics, Cornell University, Ithaca, NY, USA
[11] Department of Computer Science, Cornell University, Ithaca, NY, USA
[12] Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 München, Germany
[13] Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland

New quantum simulation platforms provide an unprecedented microscopic perspective on the structure of strongly correlated quantum matter. This allows to revisit decade-old problems from a fresh perspective, such as the two-dimensional Fermi-Hubbard model, believed to describe the physics underlying high-temperature superconductivity. In order to fully use the experimental as well as numerical capabilities available today, we need to go beyond conventional observables, such as one- and two-point correlation functions. In this talk, I will give an overview of recent results on the Hubbard model obtained through novel analysis tools: using machine learning techniques to analyze quantum gas microscopy data allows us to take into account all available information without a potential bias by the choice of an observable and compare different theories on a microscopic level. I will introduce a novel, customized neural network architecture, which features full interpretability and thus enables direct physical insights. The analysis of data from quantum simulation experiments of the doped Fermi-Hubbard model with machine learning tools as well as through different higher-order correlations shows a qualitative change in behavior around 20% doping, consistent with condensed matter experiments on cuprate materials. As an outlook, I will discuss how our microscopic understanding of the low doping limit has led us to the discovery of a binding mechanism, which enables pairing of charge carriers at currently accessible experimental temperatures, thus paving the way for the study of pair formation in cold atom quantum simulators.

Quantum firmware: optimal control for quantum simulators

T. Calarco[1]

[1]*Forschungszentrum Jülich, Germany*

Quantum optimal control has been shown to improve the performance of quantum technology devices up to their limits in terms e.g. of system size and speed of operation. This talk will review our recent results with a variety of quantum technology platforms, focusing in particular on ultracold atoms, and introduce our newly developed software for automatic calibration of quantum operations - the fundamental building block of next-generation quantum firmware.

References

[1] A. Omran et al., Science **365,** 570 (2019)
[2] M. Lam et al., Phys. Rev. X **11**, 1 (2021)
[3] F. Borselli et al., Phys. Rev. Lett. **126**, 8 (2021)

Quantum simulations: from the Fermi Hubbard model to quantum magnetism

Eugene Demler

ETH Zurich, Institute for Theoretical Physics, Zurich, Switzerland

Quantum readout using quantum gas microscopes

Jens Eisert

Freie Universität Berlin, Dahlem Center for Complex Quantum Systems, Berlin, Germany

One of the most significant challenges in quantum simulation arises from the necessity of achieving highly accurate read-out, benchmarking and calibration of quantum simulators. After all, if these tasks cannot be accomplished to high accuracy, the predictive power of quantum simulators must remain limited. In this talk, we will be faithful to the theme of the workshop and will discuss ways of performing quantum read-out using quantum gas microscopes and similar detection schemes, both in the continuum for quantum field systems [1] and for cold atoms in optical lattices [2]. In the second part of the talk, we will look at the subject from a slightly broader perspective and will show how suitable and experimentally friendly randomized measurements give rise to tools for read-out, benchmarking and calibration [3]. Starting from early work that contributed to kick-starting the randomized measurements programme [4], we will see how modern schemes bringing together ideas of randomized benchmarking [5] and shadow estimation give rise to powerful and versatile schemes for read-out, benchmarking and calibration, not only for quantum gate sets [6], but also in the continuum for analog quantum simulators [7].

[1] Communications Physics 3, 12 (2020).
[2] Phys. Rev. Lett. 127, 090503 (2021).
[3] Nature Reviews Physics 2, 382-390 (2020).
[4] New J. Phys. 15, 015024 (2013).
[5] PRX Quantum, in press (2022), arXiv:2010.07974.
[6] arXiv:2110.13178 (2021).
[7] In preparation (2022).

Self-oscillating and Floquet-driven quantum pumps

Tilman Esslinger

ETH Zürich, Switzerland

Pumps are transport mechanisms in which direct currents result from a cycling evolution of the potential. As Thouless has shown, the pumping process can have topological origins, when considering the motion of quantum particles in spatially and temporally periodic potentials. We report on two novel approaches to geometric pumping.

We discovered an emergent mechanism for geometric pumping in a quantum gas coupled to an optical resonator, where we observe a particle current without applying a periodic drive. The pumping potential experienced by the atoms is formed by the self-consistent cavity field interfering with the static laser field driving the atoms [1].

In the simple setting of a plain sinusoidal lattice potential with a two-tone Floquet drive (ω and 2ω) we demonstrate topological pumping. We adiabatically prepare a near-insulating Floquet band of ultracold fermions via a frequency chirp, which avoids gap closings en route from trivial to topological bands. Subsequently, we induce topological pumping by slowly cycling the amplitude and the phase of the 2ω drive [2].

Along a different direction we report on the experimental realization and detection of dynamical currents in a spin-textured lattice in momentum space. Collective tunneling is implemented via cavity-assisted Raman scattering of photons by a spinor Bose-Einstein condensate into an optical cavity. We observe that the individual tunneling events are superradiant in nature and locally resolve them in the lattice by performing real-time, frequency-resolved measurements of the leaking cavity field [3].

References

[1] Davide Dreon, Alexander Baumgärtner, Xiangliang Li, Simon Hertlein, Tilman Esslinger, Tobias Donner, arXiv:2112.11502

[2] Joaquín Minguzzi, Zijie Zhu, Kilian Sandholzer, Anne-Sophie Walter, Konrad Viebahn, Tilman Esslinger, arXiv:2112.12788

[3] Rodrigo Rosa-Medina, Francesco Ferri, Fabian Finger, Nishant Dogra, Katrin Kroeger, Rui Lin, R. Chitra, Tobias Donner, Tilman Esslinger, arXiv:2108.11888

Scalable quantum state tomography with artificial neural networks

T. Schmale[1,2], M. Reh[1], N. Euler[1] and M. Gärttner[1,3]

[1] *Kirchhoff-Institute for Physics, Heidelberg University, Heidelberg, Germany*
[2] *Institute for Theoretical Physics, Hannover University, Hannover, Germany*
[3] *Physikalisches Institut, Heidelberg University, Heidelberg, Germany*

Modern-day quantum simulators can prepare a wide variety of quantum states but extracting observables from the resulting "quantum data" often poses a challenge. We tackle this problem by developing a quantum state tomography scheme which relies on approximating the probability distribution over the outcomes of an informationally complete measurement in a variational manifold [1] represented by a convolutional neural network. We show an excellent representability of prototypical ground- and steady states with this ansatz using a number of variational parameters that scales polynomially in system size. This compressed representation allows us to reconstruct states with high classical fidelities outperforming standard methods such as maximum likelihood estimation. Furthermore, it achieves a reduction of the statistical error of observables by up to an order of magnitude compared to their direct estimation from experimental data [2]. In addition, I will report on a scheme for detecting high dimensional entanglement in fermionic quantum gas microscopes.

References

[1] J. Carrasquilla et al., Nature Machine Intelligence **1**, 155-161 (2019)
[2] T. Schmale, M. Reh, M. Gärttner, arXiv:2109.13776 (2021)

Orbital order and chiral currents of interacting bosons with π-flux

M. Di Liberto[1] and N. Goldman[2]

[1] *IQOQI, Innsbruck, Austria*
[2] *CENOLI, Brussels, Belgium*

Higher Bloch bands provide a remarkable setting for realizing many-body states that spontaneously break time-reversal symmetry, offering a promising path towards the realization of interacting topological phases. Here, we propose a different approach by which chiral orbital order effectively emerges in the low-energy physics of interacting bosons moving on a square plaquette pierced by a π-flux. We analyze the low-energy excitations of the condensate in terms of two orbital degrees of freedom and identify a gapped collective mode corresponding to the out-of-phase oscillations of the relative density and phase of the two orbitals. We further highlight the chiral nature of the ground state by revealing the cyclotron-like dynamics of the density upon quenching an impurity potential on a single site. Our single-plaquette results can be used as building blocks for extended dimerized lattices, as we exemplify using the BBH model of higher-order topological insulators. Our results provide a distinct direction to realize interacting orbital-like models that spontaneously break time-reversal symmetry, without resorting to higher bands nor to external drives.

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Co-designed quantum simulation of non-abelian gauge theories with Rydberg qudits

D. González-Cuadra,[1, 2, *] **T. V. Zache,**[1, 2, *] **J. Carrasco,**[3]

B. Kraus,[3] **and P. Zoller** [1, 2]

[1] *Center for Quantum Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[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*

Non-abelian gauge theories underlie our understanding of fundamental forces in nature, and developing tailored quantum hardware and algorithms to simulate them is an outstanding challenge in the rapidly evolving field of quantum simulation. Here we take an approach where gauge fields, discretized in space and time, are represented by qudits, and are time-evolved in Trotter steps with multi-qudit quantum gates. This maps naturally and hardware-efficient to an architecture based on Rydberg tweezer arrays, where long-lived internal atomic states represent qudits, and the required quantum gates are performed as error-tolerant holonomic operations supported by a Rydberg blockade mechanism. We illustrate our proposal for a minimal digitization of SU(2) gauge fields, where we also demonstrate how to verify the quantum simulation using Hamiltonian learning techniques.

[*] These authors contributed equally.

Ultracold Atom Quantum Simulations: From Fermi-Hubbard to Fractional Quantum Hall Physics

Markus Greiner

Harvard University, Department of Physics, Cambridge, MA, USA

Ultracold atom quantum simulations offer the unique opportunity to experimentally address outstanding problems in many-body quantum physics. Quantum gas microscopy brings this effort to the ultimate level of single particle control. I will present recent work on Fermi Hubbard systems, strongly interacting bosons in artificial gauge fields, and quantum dynamics.

The low-temperature challenge in optical lattices

C. Groß[1]

[1]Physikalisches Institut, Eberhard Karls Universität Tübingen, 72076 Tübingen, Germany

One of the most important challenges for fermionic systems in optical lattices is the quest for low temperatures. Only at temperatures below a few percent of the Fermi temperature correlation lengths become sizeable. This is the regime in which the system behaves highly collective, and where new quantum phases are expected to emerge. Despite significant progress in the recent years, the required temperatures have remained out of reach in optical lattices. Here we present a new experiment with a mixture of erbium and lithium atoms designed for optimized sympathetic cooling in optical lattices. We discuss the unique features of this surprisingly little explored mixture and present the current status of our new experimental setup designed to challenge the low-temperature frontier.

Enhancing disorder-free localization through dynamically emergent local symmetries

J. C. Halimeh[1,2], L. Homeier[1,2,3], H. Zhao[4,5], A. Bohrdt[6,3], F. Grusdt[1,2], P. Hauke[7], and J. Knolle[8,2,5]

[1] Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany
[2] Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany
[3] Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[4] Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Straße 38, 01187 Dresden, Germany
[5] Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom
[6] ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[7] INO-CNR BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy
[8] Department of Physics, Technische Universität München, James-Franck-Straße 1, D-85748 Garching, Germany

Disorder-free localization is a recently discovered phenomenon of nonergodicity that can emerge in quantum many-body systems hosting gauge symmetries when the initial state is prepared in a superposition of gauge superselection sectors. Thermalization is then prevented up to all accessible evolution times despite the model being nonintegrable and translation-invariant. In a recent work [Halimeh, Zhao, Hauke, and Knolle, arXiv:2111.02427], it has been shown that terms linear in the gauge-symmetry generator stabilize disorder-free localization in U(1) gauge theories against gauge errors that couple different superselection sectors. Here, we show in the case of Z_2 gauge theories that disorder-free localization can not only be stabilized, but also *enhanced* by the addition of translation-invariant terms linear in a local Z_2 *pseudogenerator* that acts identically to the full generator in a single superselection sector, but not necessarily outside of it. We show analytically and numerically how this leads through the quantum Zeno effect to the dynamical emergence of a renormalized gauge theory with an enhanced local symmetry, which contains the Z_2 gauge symmetry of the ideal model, associated with the Z_2 pseudogenerator. The resulting proliferation of superselection sectors due to this dynamically emergent gauge theory creates an effective disorder greater than that in the original model, thereby enhancing disorder-free localization. We demonstrate the experimental feasibility of the Z_2 pseudogenerator by providing a detailed readily implementable experimental proposal for the observation of disorder-free localization in a Rydberg setup.

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Emergence of many body physics, atom by atom

Selim Jochim

Physikalisches Institut, Heidelberg University, Germany

We prepare samples of up to 20 fermionic atoms with ultralow entropies in a two-dimensional configuration. We developed a single atom and spin sensitive imaging technique that allows us to detect all atoms of a sample either in real or in momentum space. From such measurements we can infer correlations in the system. In our fermonic system, these are present already in a noninteracting sample and give rise to so-called Pauli Crystals [1]. More interesting correlations arise as soon as interactions in the system are turned on. Now, Cooper pairs and a BCS-like system can be observed to form with ***p,-p*** - correlations emerging at the Fermi surface [2]. In our trapped finite system, pairing occurs only at a finite attraction strength, which results in the precursor of a quantum phase transition [3]. To further understand the emergence of many body physics from the few-body limit we are currently exploring a single impurity in a finite Fermi sea to observe the transition from a molecular to a polaronic state.

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New frontiers in atom arrays and quantum gas microscopes using alkaline-earth atoms

Adam Kaufmann

JILA/NIST, Boulder, Co, USA

Quantum science with neutral atoms has seen great advances in the past two decades. Many of these advances follow from the development of new techniques for cooling, trapping, and controlling atomic samples. As one example, the technique of optical tweezer trapping of neutral atom arrays has been a powerful tool for quantum simulation and quantum information, because it enables scalable control and detection of individual atoms with switchable interactions. In this talk, I will describe ongoing work at JILA where we have explored a new type of atom - two-electron atoms - for optical tweezer trapping. While the increased complexity of these atoms leads to challenges, they also offer new scientific opportunities by virtue of their rich internal degrees of freedom. Accordingly, they have impacted multiple areas in quantum science, ranging from quantum information processing to quantum metrology. I will report on my group's progress in these areas, and, in particular, on a new bottom-up modality for preparing atom arrays in a Hubbard-regime lattice using optical tweezers.

Machine Learning for Quantum Simulation

Eun-Ah Kim[1]

[1] *Cornell University, Ithaca, USA*

Recent advances in quantum simulator technology have opened up a new era in exploring strongly correlated matter by providing atomic-level resolution of many-body quantum states. This new experimental modality produces large and complex projective measurement datasets which are difficult to analyze using traditional methods and calls for modern data-centric computational analysis techniques.
Building on the supervised machine learning technique we developed for quantum gas microscopy [1], Correlation Convolutional Neural Network (CCNN), we introduce a hybrid unsupervised-supervised machine learning approach (Hybrid-CCNN). Hybrid-CCNN applied to a comprehensive dataset of quantum snapshots from a 256-qubit Rydberg simulator revealed novel quantum correlations in the striated phase and discovered two new phases: boundary ordered phase and rhombic phase[2]. The capability to discover phase transitions and cross-overs and reveal new insight through its interpretability promises the potential for Hybrid-CCNN to contribute to furthering quantum simulations' frontiers.

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Driven or dissipative impurities in fermionic quantum gases

Corina Kollath

Universität Bonn, Germany

By the extended demand for the miniaturization of technical devices as transistors, nowadays a large effort is made in order to engineer quantum devices which work at the few particle level. Whereas in earlier studies mainly steady state working principles have been investigated,during the last decade also the dynamic shaping and controlling of such devices attracted an increasing attention. We present here some of the fascinating features of driven or dissipative impurities.

Fermionic superfluids in two and three dimensions

Lennart Sobirey, Niclas Luick, Markus Bohlen, Hauke Biss, Thomas Lompe, <u>Henning Moritz</u>

Institut für Laserphysik, Universität Hamburg, Germany

In this talk, I will review our recent work on superfluidity in homogeneous 2D and 3D Fermi gases. In the first part I will report on the observation of Josephson oscillations between two such gases [1], demonstrating phase coherence between them, enabling us to find excellent agreement with the sinusoidal current phase relation of an ideal Josephson junction and determine the critical current.

In the second part I will present our measurements of the dynamic structure factor of 2D [2,3] and 3D [4] superfluids. Using Bragg spectroscopy, we determine the critical velocity and the superfluid gap in the BEC-BCS crossover, allowing for detailed comparisons with and benchmarks for theory. Our measurements enable us to directly study the role of reduced dimensionality on strongly correlated superfluids.

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Quantum Field Simulator –Universal Time Dynamics & Relativistic Fields in Ultracold Gases

Markus Oberthaler

Heidelberg University, Kirchhoff-Institute for Physics, Heidelberg, Germany

Ultracold gases offer an experimental platform with pristine control of parameters as well as unique readout capabilities making new observables experimentally accessible. In this talk, I will present two experimental implementations of a quantum field simulator.

Utilizing a Rubidium spinor condensate, we investigate the question about the emergence of universal time dynamics. The new POVM readout [1] allows for the spatially resolved detection of the complex order parameter of the easy-plane ferromagnet, a prerequisite for clear demonstration of universal time dynamics [2], the extraction of the quantum effective action [3] and the detection of entanglement structure in real space [4]. I will present our latest results revealing the existence of two distinct non-thermal fixed points in the same Hamiltonian system. We find the corresponding universal functions and exponents characterizing the underlying structures.

With the platform of a two-dimensional ultracold potassium gas, we implement an action describing a free relativistic scalar field in the quantum limit with full control, in space and time, of the underlying metric [5]. We demonstrate quantum wave packet dynamics in hyperbolic and spherical spatial geometry clearly revealing the curvature. Extending the concept of curvature to time we confirm the expected particle production. Building on the unique readout capabilities, we not only access the number of generated particles but also for the first time the phase of the excitation amplitudes. The quantitative agreement with new analytical predictions for time dependent metrics benchmarks the simulator and with that establishes the new class of quantum field simulators implementing relativistic quantum actions.

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Time-of-flight quantum tomography of single atom motion in an optical tweezer

M. O. Brown[1], S. R. Muleady[1], W. J. Dworschack[1], R. J. Lewis-Swan[2], A. M. Rey[1], O. Romero-Isart[3], and C. A. Regal[1]

[1]JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309, USA
[2]Homer Dodge Dept of Physics and Astronomy, University of Oklahoma, Norman, OK 73019
[3]Institute for Theoretical Physics, University of Innsbruck, A-6020 Innsbruck, Austria

I will discuss experiments with ^{87}Rb atoms in optical tweezers in which we use time-of-flight imaging to demonstrate full tomography of a non-classical motional state. By combining time-of-flight imaging with coherent evolution of an atom in the optical tweezer, we are able to access arbitrary quadratures in phase space without relying on coupling to a spin degree of freedom. To create non-classical motional states, we using tunneling in the potential landscape of optical tweezers, and our tomography both demonstrates Wigner function negativity and assesses coherence of non-stationary states. We are motivated to explore this tomography method for its broad applicability to other neutral particles, such as large-mass dielectric spheres.

I will also provide a brief description of our broader optical tweezer work focused on studying light-assisted collisions and on extending atom lifetimes with a new cryogenic optical tweezer array apparatus.

Observation and control of elastic p-wave interactions between fermions in an optical lattice

A. M. Rey

JILA, NIST and Department of Physics, University of Colorado, Boulder, USA

P-wave interactions can give rise to non-conventional superconductors and superfluids that feature non-trivial transport properties. Their realization in fully controllable quantum systems, such as ultracold fermionic atoms, would enable topological qubits and new types of quantum simulations. However, p-wave interactions are weak in naturally occurring systems, and their enhancement via Feshbach resonances in ultracold systems has been limited by three-body loss. In this talk we discuss theoretical and experimental investigations that use isolated pairs of spin-polarized fermionic atoms in two different orbitals in a three-dimensional optical lattice to suppress detrimental three-body losses. We report the first direct observation of strong elastic p-wave interactions all the way into the unitary regime. By controlling the interaction strength via a magnetic field and lattice confinement, we spectroscopically measure elastic interactions of p-wave pair states near the magnetic Feshbach resonance and measure their lifetime to be up to ten times larger than that of a free-space dimer. We take the first steps towards coherent control via Rabi oscillations between free-atoms and Feshbach molecules. We finally discuss prospects for the observation of nonequilibrium orbital physics in this system and identify a regime where p-wave induced collective dynamics and entanglement can emerge.

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Tunneling transport of strongly interacting Fermi gases across the superfluid transition

G.Roati[1]

[1]CNR-INO and LENS, Sesto Fiorentino, Italy

Tunneling transport measurements provide a powerful tool to unveil the coherence properties of a many-body system. Here, I present our results on the dynamics of fermionic superfluids weakly-coupled through a tunable tunneling barrier. In the absence of any applied chemical potential difference, we measure the Josephson critical current and we extract the condensed fraction of fermionic superfluids [1]. We then characterise the operation of our atomic junction across the superfluid transition. We find that Josephson supercurrents vanish when approaching the critical temperature due to condensate depletion. Remarkably, we observe the condensate to contribute also to resistive currents through the coupling with Bogoliubov-Anderson phonons [2].

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Emergent Quantum Simulators

<u>Jörg Schmiedmayer</u>
Vienna Center for Quantum Science and Technology (VCQ), Atominstitut, TU-Wien

Quantum Simulation promises insight into quantum physics problems which are beyond the ability to calculate with conventional methods. Quantum simulators can be built either using a ***'digital'*** Trotter decomposition of the problem or by directly building the Hamiltonian in the lab and performing ***'analogue'*** experiments. I will present here a different approach, by which the model to simulate ***emerges naturally*** from a completely different microscopic Hamiltonian. I will illustrate this in the example of the emergence of the Sine-Gordon quantum field theory from the microscopic description of two tunnel coupled super fluids [1] and in the emergence of Pauli blocking in an weakly interacting bose gas [2]. Special emphasis will be put on how to verify such emergent quantum simulators and how to characterize them. Thereby I will present two tools: High order correlation functions and their factorization [1], the evaluation of the quantum effective action and the momentum dependence of propagators and vertices (running couplings, renormalization of mass etc ..) of the emerging quantum field theory [3] and quantum field tomography that points to a new way to read out quantum simulators [4]. Together they establish general methods to analyse quantum systems through experiments and thus represents a crucial ingredient towards the implementation and verification of quantum simulators.

Work performed in collaboration with the groups of Th. Gasenzer und J. Berges (Heidelberg), Jens Eisert (FU Berlin) and E. Demler (Harvard). Supported by the DFG-FWF: SFB ISOQUANT: and the EU: ERC-AdG *QuantumRelax*

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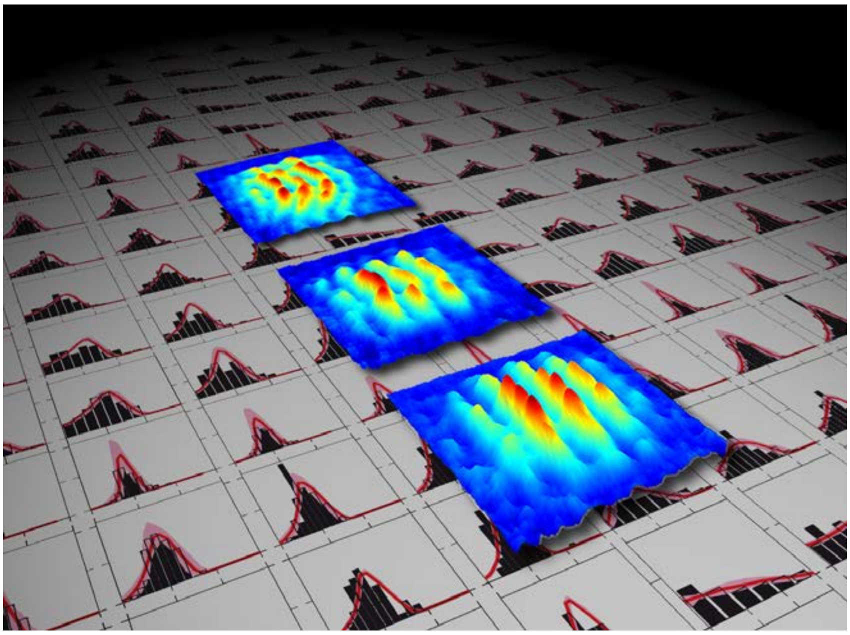

Quantum geometry and superfluidity in moiré superlattices and ultracold gas systems

K.-E. Huhtinen[1], S. Peotta[1], A. Julku[1,2], P. Kumar[1], V.A.J. Pyykkönen[1], G.M. Bruun[2], Y. Takasu[3], Y. Takahashi[3], P. Fabritius[4], J. Mohan[4], T. Esslinger[4], and P. Törmä[2]

[1]Department of Applied Physics, Aalto University, Helsinki, Finland
[2] Center for Complex Quantum Systems, Department of Physics and Astronomy, Aarhus University, Denmark
[3] Department of Physics, Kyoto University, Japan
[4] Department of Physics, ETH Zurich, Switzerland

Quantum geometry, namely quantities such as quantum metric, Berry curvature, and Chern number, have become increasingly important in understanding interacting many-body systems in solid state and ultracold gas quantum matter. We have shown that supercurrents and superfluidity in a flat band are governed by quantum geometry [1], which opens new prospects for achieving high temperature superconductivity. These findings have become relevant for superconductivity in twisted bilayer graphene and ultracold gas moiré materials [2]. We present our newest results on the topic, showing that to achieve the critical temperature enhancement, the flat band does not need to be isolated from other bands, which is promising from the experimental perspective [3]. We discuss how interesting flat band effects both in the normal and superconducting states could be observed in ultracold gas systems, with quantum gas microscopes or transport experiments [4,5,6]. Further, we show that quantum geometry governs the behaviour of bosonic condensates in flat bands as well, making quantum fluctuation effects remarkably strong [7].

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Microscopy of quantum correlations in an ultracold molecular gas

Z. Z. Yan, J. S. Rosenberg, L. Christakis, R. Raj, S. Chi, E. Guardado-Sanchez, W. S. Bakr

[1]Princeton University, Princeton, NJ, USA
zzyan@princeton.edu

Ultracold molecules represent a powerful platform for quantum simulation and quantum computation due to their rich and controllable internal degrees of freedom. However, the detection of correlations between single molecules in an ultracold gas has not been previously demonstrated. I will present our observation of the Hanbury Brown and Twiss effect with bosonic NaRb Feshbach molecules, in which we detect bunching correlations in the density fluctuations of a 2D molecular gas released from and subsequently recaptured in an optical lattice. I will also discuss recent work studying molecules transferred to the absolute ground state, where they possess a large permanent electric dipole moment. By preparing the molecules in long-lived superpositions of the ground and first excited rotational states, we realize a 2D quantum XY model with long-range interactions. Using a site-resolved Ramsey interferometric technique, we detect oscillations in nearest- and next-nearest-neighbor correlations due to spin interactions. The techniques presented here open new doors for probing quantum correlations in complex many-body systems of ultracold molecules.

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A Landau Theory for Spin Squeezing

N. Yao[1,2]

[1]UC Berkeley, USA
[2] Harvard University, USA

The dynamical generation of spin squeezing is well known to arise from the so-called one-axis-twisting model – an all-to-all coupled Ising Hamiltonian. Motivated by recent advances in a variety of quantum simulation platforms, there has been tremendous interest in the possibility of generating spin squeezing via Hamiltonians which do not require all-to-all interactions. This interest has centered on a class of power-law interaction models, corresponding to long-ranged generalizations of the paradigmatic XXZ Hamiltonian. We conjecture that optimal spin squeezing in such models is intimately connected to the presence of finite-temperature, continuous symmetry breaking order (i.e. easy-plane ferromagnetism). In particular, we prove that if the temperature of the initial product state is above Tc, the system will not exhibit scalable squeezing.

Entanglement Spectroscopy and probing the Li-Haldane Conjecture in Topological Quantum Matter

T. V. Zache[1,2], **C. Kokail**[1,2], **B. Sundar**[1,3], **and P. Zoller**[1,2]

[1] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck 6020, Austria*

[2] *Center for Quantum Physics, University of Innsbruck, Innsbruck 6020, Austria*

[3] *JILA, Department of Physics, University of Colorado, Boulder CO 80309, USA*

Topological phases are characterized by their entanglement properties, which is manifest in a direct relation between entanglement spectra and edge states discovered by Li and Haldane. In this talk, I will present our proposal [1] to leverage the power of synthetic quantum systems for measuring entanglement via the Entanglement Hamiltonian to probe this relationship experimentally. This is made possible by exploiting the quasi-local structure of Entanglement Hamiltonians. I will illustrate the feasibility of this approach for two paradigmatic examples realizable with current technology, an integer quantum Hall state of non-interacting fermions on a 2D lattice and a symmetry protected topological state of interacting fermions on a 1D chain. These results pave the road towards an experimental identification of topological order in strongly correlated quantum many-body systems.

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Optical tweezer arrays of polar molecules from the bottom-up

Jessie T. Zhang[1], Lewis R. B. Picard[1], William B. Cairncross[1], Gabriel Patenotte[1], Kenneth Wang[1], Yichao Yu[1], Fang Fang[1], Kang-Kuen Ni[1]

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

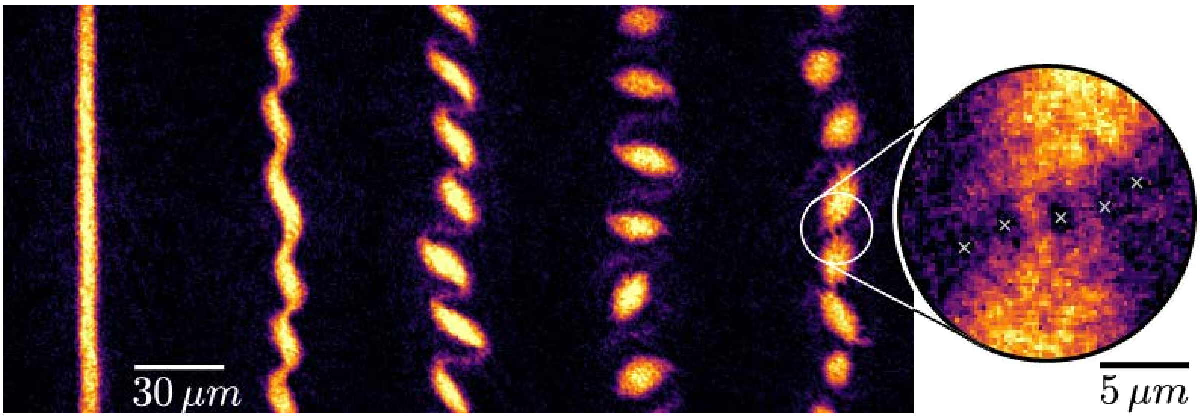
Ultracold polar molecules, compared to their ultracold atom counterparts, possess rich internal structures and exhibit long-range dipole-dipole interactions that render them useful for many applications such as quantum simulation of matter, quantum computation and precision measurements. At the heart of many of these proposals is the ability to trap and control ultracold molecules at the individual particle level. In this talk, I will discuss how we assemble arrays of single polar molecules from ultracold atoms trapped in optical tweezers, and our recent efforts towards entangling pairs of molecules in an array. This bottom-up approach utilizes laser cooling and trapping techniques of ultracold atoms and has enabled us to achieve full quantum state control, including all the internal and external degrees of freedom, on individually trapped molecules in an array. This opens up many exciting possibilities that can harness the rich properties of ultracold molecules.

Quantum Register of Fermion Pairs and Crystallization of Bosonic Quantum Hall States

M. Zwierlein[1]

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

I will discuss two recent quantum gas experiments at MIT: The demonstration of a quantum register made of fermion pairs and the crystallization of bosonic quantum Hall states. The "glue" between these rather orthogonal topics is the harmonic oscillator that underlies these experiments. For the quantum register we observed long-lasting coherence of the relative and center-of-mass motion of fermion pairs, which may serve as a novel type of qubit. In the work on rotating quantum gases, we empoly a harmonic trap to perfectly cancel the centrifugal force in the rotating frame, so as to be able to observe the pure evolution of a bosonic quantum Hall state – a Landau gauge wavefunction – in "flat land" - under the sole influence of interactions and the effective magnetic field provided by the Coriolis effect. We observe that this wavefunction is unstable against crystallization, and show that the instability smoothly connects from the quantum regime to the classical description of a Kelvin-Helmholtz-like instability of counterflow.



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Quantum Register of Fermion Pairs
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Crystallization of Bosonic Quantum Hall States
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Abstracts of Posters

(in alphabetical order)

Canonically consistent master equation

Tobias Becker,[1] Alexander Schnell,[1] and Juzar Thingna[2]

[1] *Institute für Theoretische Physik, Technische Universität Berlin, Hardenbergstr. 36, D-10623 Berlin, Germany*

[2] *Center for Theoretical Physics of Complex Systems, Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea*

We put forth a new class of quantum master equations that correctly reproduce the asymptotic state of an open quantum system beyond the infinitesimally weak system-bath coupling limit. Our method is based on incorporating the knowledge of the reduced asymptotic state in its dynamics. The correction not only steers the reduced system dynamics towards a correct asymptote but also improves its temporal accuracy, thereby refining the archetypal weak-coupling quantum master equations. In case of equilibrium, since a closed form for the asymptote exists in terms of a generalized Gibbs state, we utilize this form to correct the celebrated Redfield quantum master equation. Using an exactly solvable harmonic oscillator system we corroborate our approach with the exact solution obtained via path integral formulation showing that our method also helps correcting the long-standing issue of negative populations, albeit without complete positivity. Our method sets a new milestone in the theory of open quantum systems wherein our time-dependent reduced density matrix is accurate beyond the infinitesimally weak coupling regime and goes beyond the accuracy of commonly used Redfield and Lindblad equations.

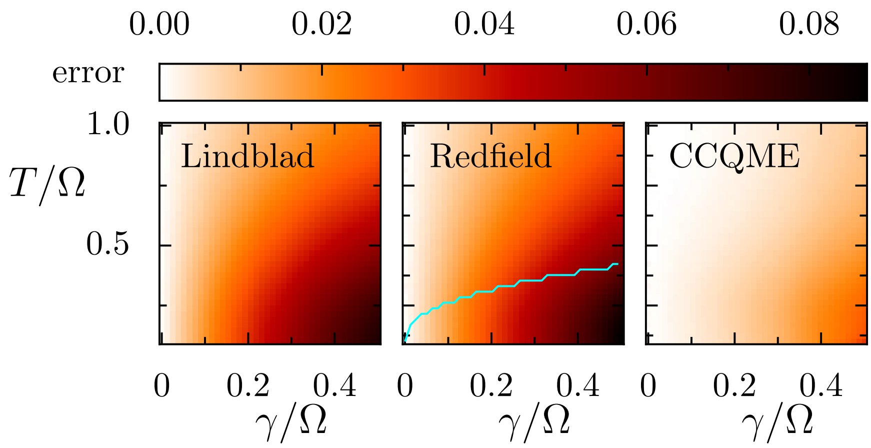

FIG. 1: Error for three different master equations, i.e. secular Lindblad, Redfield and our proposed canonically consistent master equation, as a function of coupling strength and temperature. We show the trace distance to the exact steady state solution for the Caldeira Leggett model of the damped harmonic oscillator where we consider an Ohmic thermal bath with Drude cutoff. Below the bright line the Redfield steady state acquires negative populations.

Prethermalization in confined spin chains

Stefan Birnkammer[1,2], **Alvise Bastianello**[1,2] **and Michael Knap**[1,2]

[1]*Department of Physics, Technical University of Munich, 85748 Garching, Germany*
[2]*Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany*

Unconventional nonequilibrium phases with restricted correlation spreading and slow entanglement growth have been proposed to emerge in systems with confined excitations, calling their thermalization dynamics into question. Here, we investigate the many-body dynamics of a confined Ising spin chain, in which domain walls in the ordered phase form bound states reminiscent of mesons. We show that the thermalization dynamics after a quantum quench exhibits multiple stages with well separated time scales. The system first relaxes towards a prethermal state, described by a Gibbs ensemble with conserved meson number. The prethermal state arises from rare events in which mesons are created in close vicinity, leading to an avalanche of scattering events. Only at much later times a true thermal equilibrium is achieved in which the meson number conservation is violated by a mechanism akin to the Schwinger effect.

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Fractional quantum Hall states near the first Mott lobe

Julian Boesl, **Rohit Dilip, Frank Pollmann, and Michael Knap**

Department of Physics and Institute for Advanced Study, Technical University of Munich, 85748 Garching, Germany
Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, 80799 München, Germany
E-mail: julian.boesl@tum.de

The Bose-Hubbard model subjected to an effective magnetic field hosts a plethora of phases with different topological orders when tuning the chemical potential. Using the density matrix renormalization group method, we identify several gapped phases near the first Mott lobe at strong interactions. They are connected by a particle-hole symmetry to a variety of quantum Hall states stabilized at low fillings. We characterize phases of both particle and hole type and identify signatures compatible with Laughlin, Moore-Read, and bosonic integer quantum Hall states by calculating the quantized Hall conductance and by extracting the topological entanglement entropy. Furthermore, we analyze the entanglement spectrum of Laughlin states of bosonic particles and holes for a range of interaction strengths, as well as the entanglement spectrum of a Moore-Read state. These results further corroborate the existence of topological states at high fillings, close to the first Mott lobe, as hole analogs of the respective low-filling states.

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Towards a strontium quantum gas microscope

S. Buob[1], J. Höschele[1], D. Jacobs[1], A. Rubio-Abadal[1], V. Makhalov[1] and L. Tarruell[1]

[1]ICFO – Institut de Ciencies Fotoniques,
The Barcelona Institute of Science and Technology,
08860 Castelldefels (Barcelona), Spain
E-mail: sandra.buob@icfo.eu

Quantum gas microscopy presents a powerful tool for studying microscopic phenomena of complex many-body quantum systems. In the recent years, many fascinating results have been achieved exploiting the single-site resolution available in this kind of setups. The possibilities of quantum gas microscopes combined with the properties of earth-alkaline atoms promises access to new physical systems and phenomena.

In our experiment, we aim at the realization of a quantum gas microscope with strontium, i.e. trapping strontium in optical lattices with single-site resolved imaging. The rich level structure of strontium offers a wide range of possibilities in the context of quantum gas microscopes. The broad transition at 461 nm with linewidth of $\Gamma/2\pi$ = 32 MHz allows fast imaging, and the narrow-linewidth transition ($\Gamma/2\pi$ = 7 kHz) in the red spectrum enables cooling of the atoms during their detection. The planned optical lattice at magic-wavelength with a lattice spacing of 575 nm will facilitate the realization of single-site resolution. Furthermore, it will enable us to investigate collective light scattering in the subradiant regime thanks to the “perfect” two-level system present in bosonic strontium. Moreover, the millihertz transition of fermionic strontium makes it possible to selectively shelve spin components in the long-lived clock state and implement spin-resolved imaging. This will be convenient for studying many-component SU(N)-Fermi systems which strontium gives access to. For instance, the large nuclear spin of strontium combined with the single spin and site resolved imaging will enable us to study magnetic ordering of systems with up to ten different spin states in unit-filled optical lattices.

In my poster, I am going to present the current state of the machine. In particular, the experimental setup and the cooling process of strontium to reach quantum degeneracy for the different isotopes. As an outlook, I will present the planned optical lattice, the imaging system and the future directions of our research.

Fast long-distance transport of cold cesium atoms

T. Klostermann, C. R. Cabrera, H. von Raven, J. F. Wienand, C. Schweizer, I. Bloch, M. Aidelsburger

[1] Fakultät für Physik, Ludwig-Maximilians-Universität, Schellingstr. 4, D-80799 München, Germany
[2] Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany
[3] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
[4] Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, D-85748 Garching, Germany

The fundamental properties of matter are generally well described in terms of the underlying symmetries of the system. However, the discovery of the quantized Hall conductivity marked the beginning of a new classification of phases of matter and phase transitions of materials: Topological insulators (TIs). At present, band theory models describe the physics of non-interacting topological insulators; nevertheless, the rich and still not well-understood connection between topology and interactions represent a new paradigm in modern condensed matter physics.

In my poster, I will report on the construction of a new quantum gas microscope experiment with bosonic Cesium atoms to study strongly correlated topological phases. I will present a novel technique for the production of a Cs Bose-Einstein condensate after a fast, long-distance optical transport, and the most recent results on single-atom resolution in a 2D optical lattice. I will discuss the implementation of artificial neural networks as a tool to reach single-site resolution and high fidelity reconstruction of the lattice occupation. Finally, I will present the next steps towards the observation of a higher-order symmetry-protected topological phase: the 2D Su-Schrieffer-Heeger model.

Towards an erbium-dysprosium quantum gas microscope

E. Casotti[1], L. Klaus[1], C. Politi[1,2], M. Sohmen[1,2], M. A. Norcia[2], M. J. Mark[1,2], F. Ferlaino[1,2]

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

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

In the last two decades, ultracold atoms in optical lattices have been established as a powerful toolbox for quantum optics, enabling the study of many-body physics and the simulation of strongly correlated condensed matter. More recently, a new window on the physics of these systems has been opened by the experimental realization of quantum gas microscopes, which allow single-site imaging and addressing of the atoms. So far, quantum gas microscopes have been realized with atomic species with a negligible magnetic moment, which interact only via short-range contact interaction. On the other hand, the presence of direct-long range interaction between neighboring atoms would lead to the observation of a wealth of other effects. In this perspective, strongly magnetic atomic species like erbium and dysprosium are promising candidates, as they combine simple cooling techniques with low losses. Three-dimensional bulk quantum gases of erbium and dysprosium confined in the direction of the dipole polarization have already shown the effect of the interplay between contact interaction, dipole-dipole interaction, and fluctuations, which can lead to spontaneous density modulated states [1-3]. Additionally, some effects of long-range interactions in the lattice have already been studied for ^{167}Er with TOF techniques [4, 5]. Here, we report on the progress towards a quantum gas microscope for erbium and dysprosium, which would allow the study of both single species and mixture physics in a directly accessible way. With this new setup, we aim to probe extended Bose-Hubbard and extended Fermi-Hubbard models, entering a new quantum simulation framework, unachievable by conventional short-range interaction lattices.

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Self-ordered Time Crystals: Periodic Temporal Order under Quasiperiodic Driving

Sayan Choudhury and W. Vincent Liu

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, USA

E-mail: sayan.choudhury@pitt.edu

A discrete time crystal is a remarkable non-equilibrium phase of matter characterized by persistent sub-harmonic response to a periodic drive. Motivated by the question of whether such time-crystalline order can persist when the drive becomes aperiodic, we investigate the dynamics of a Lipkin-Meshkov-Glick model under quasiperiodic kicking. Intriguingly, this infinite-range interacting spin chain can exhibit long-lived periodic oscillations when the kicking amplitudes are drawn from the Thue-Morse sequence (TMS). We dub this phase a "Self-ordered time crystal" (SOTC) and demonstrate that our model hosts at least two qualitatively distinct prethermal SOTC phases. These SOTCs are robust to various perturbations, and they originate from the interplay of long-range interactions and the recursive structure of the TMS. Our results suggest that quasiperiodic driving protocols can provide a promising route for realizing novel non-equilibrium phases of matter in long-range interacting systems.

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Green’s function approach to the Bose-Hubbard model with disorder

R. S. Souza[1] , A. Pelster[2] and F. E. A. dos Santos[1]

[1] *Departamento de Física, Universidade Federal de São Carlos, 13565-905 São Carlos, SP, Brazil*

[2] *Physics Department and Reseach Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany*

The disordered Bose-Hubbard model (DBHM) describes spinless bosons with short-range interactions submitted to a random potential. This model is used to predict the superfluid-insulator phase transition. However, the position of both Mott and Bose-glass ground states in the insulating part of phase diagram is not well characterized. We present the findings obtained in [1], where we investigated the criteria for identifying the different ground states of the DBHM at finite temperatures and for small values of the tunneling energy. To this end we constructed a perturbative expansion to the single-particle Green's function. By summing tree-level contributions of the approximation, we obtained the condition to the long-range correlations which leads to the phase boundary between superfluid and insulating phases. We then obtained a renormalized expression to the local density of states, which unambiguously distinguishes the Mott-insulator and Bose-glass phases. As a result, we constructed the phase diagram considering bounded on-site disorder where the region occupied by each ground state can be identified.

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Topological phonons
in arrays of ultracold dipolar particles

M. Di Liberto[1], A. Kruckenhauser[1,2], P. Zoller[1,2] and M. A. Baranov[1,2]

[1]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck, Austria
[2] Center for Quantum Physics, University of Innsbruck, Innsbruck, Austria

The notion of topology in physical systems is associated with the existence of a nonlocal ordering that is insensitive to a large class of perturbations. This brings robustness to the behaviour of the system and can serve as a ground for developing new fault-tolerant applications. We discuss how to design and study a large variety of topology-related phenomena for phonon-like collective modes in arrays of ultracold polarized dipolar particles. These modes are coherently propagating vibrational excitations, corresponding to oscillations of particles around their equilibrium positions, which exist in the regime where long-range interactions dominate over single-particle motion. We demonstrate that such systems offer a distinct and versatile tool to investigate topological effects that can be accessed by choosing the underlying crystal structure and by controlling the anisotropy of the interactions. Our results show that arrays of dipolar particles provide a promising unifying platform to investigate topological phenomena with phononic modes.

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Towards ultracold atoms in a kagome optical lattice with single-site-resolved imaging

L. Donini[1], M. Melchner Von Dydiowa[1], D.G. Reed[1], S. Shanokprasith[1], M. Hasan[1], T. Harte[1], and U. Schneider[1]

[1]*Cavendish Laboratory, Department of Physics, University of Cambridge, UK*

We are building a quantum simulator to study ultracold atoms in an optical kagome lattice [1]. This lattice displays strong geometric frustration, which results in a flat band. For fermions, this makes the kagome antiferromagnet a candidate for studying the quantum spin liquid phase. For bosons, frustration has been predicted to e.g. give rise to interaction-driven condensation [2] and a supersolid state [3]. Since the flat band is the highest-lying subband, we access it by creating a negative absolute temperature state [4]. Our experiment is capable of cooling bosonic ^{87}Rb and ^{39}K and fermionic ^{40}K to quantum degeneracy, thus enabling studies of strongly correlated physics in bosons, fermions, and mixtures.

We implement the kagome lattice by superimposing onto a triangular lattice of 532nm light a honeycomb lattice of 1064nm light, which effectively cancels out every fourth lattice site of the triangular lattice. Our quantum simulator is therefore capable of performing experiments with the triangular and honeycomb lattices as well.

In addition to momentum-resolved imaging via time-of-flight, the apparatus will include a quantum gas microscope (QGM), enabling access to local observables.

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Certification of High-Dimensional Entanglement in Ultracold Atom Systems

Niklas Euler[1,2] and Martin Gärttner[1,2,3]

[1] *Physikalisches Institut, INF 226, 69120 Heidelberg, Germany*
[2] *Kirchhoff-Institut für Physik, INF 227, 69120 Heidelberg, Germany*
[3] *Institut für Theoretische Physik, Philosophenweg 16, 69120 Heidelberg, Germany*

Quantum entanglement has been identified as a crucial concept underlying many intriguing phenomena in condensed matter systems. Recently, instead of considering mere quantifiers of entanglement like entanglement entropy, the study of entanglement structure in terms of the entanglement spectrum has shifted into focus, leading to new insights into topological phases and many-body localization, among others. What remains a challenge is the experimental detection of such fine-grained properties of quantum systems. Here we present a method to bound the width of the entanglement spectrum or entanglement dimension of cold atoms in lattice geometries, requiring only measurements in two experimentally accessible bases and utilizing single-atom resolved readout and ballistic time-of-flight (ToF) expansion. Building on previous proposals for entanglement certification for photon pairs, we first consider entanglement between two atoms of different atomic species and later generalize to higher numbers of atoms per species and multispecies configurations showing multipartite high-dimensional entanglement. Through numerical simulations of a Fermi-Hubbard system we demonstrate that our method is robust against typical experimental noise effects and that the required measurement statistics is manageable.

Building a strontium quantum gas microscope to study the Bose-Hubbard out-of-equilibrium dynamics

Romaric Journet[1], Clémence Briosne-Fréjaville[1], Anaïs Molineri[1], Sayali Shevate[1], <u>Félix Faisant</u>,[1] Florence Nogrette[1], and Marc Cheneau[1]

[1]Université Paris-Saclay, Institut d'Optique Graduate School, CNRS, Laboratoire Charles Fabry, 91127, Palaiseau

We present the progress on the build of our strontium quantum gas microscope. At the moment, we are able to load the crossed-tweezers optical dipole trap for transport and we expect to produce a BEC of strontium 84 in the near future.
Numerical studies of lateral sideband cooling during imaging have been performed.
Our goal is to study the out-of-equilibrium dynamics near the quantum critical point of the Bose-Hubbard model, especially the propagation of excitations in the system after a quench.

Combining quantum computation and simulation on a single platform

R. Groth, A. von Haaren, J. Qesja, M. Schattauer, I. Bloch, T. Hilker, P. Preiss,

Max Planck Institute of Quantum Optics, Garching, Germany

Neutral atoms hold enormous potential for quantum computation due to their long coherence times, favorable scalability and the availability of precision techniques for state manipulation. Yet the use of quantum gas microscopes has so far been limited to analogue quantum simulation, mainly due to the inability to perform fundamental two-qubit operations. We propose the design of a novel Fermionic quantum gas microscope – called FermiQP – which combines analogue quantum simulation and digital quantum computation on a single platform. Building on previously developed techniques, the microscope will feature imaging and addressing at the single-atom level as well as spin-resolved state detection. The supplementary digital mode of operation will be facilitated via collision gates, which have already been characterized at a global level[1,2], but for which a microscopic investigation remains elusive. By means of two-qubit operations, the entanglement of the many-body system becomes programmable – hence extending the Hilbert space of initial states that are accessible for quantum simulation. Leveraging the advantages of both neutral atoms and quantum gas microscopy, this new experiment will provide a novel platform for quantum computation with its digital mode of operation, while at the same time creating new opportunities for quantum simulation via its enhanced analogue mode.

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A New Apparatus for High Cycle Rate Experiments using Lithium-6

T. Hammel[1], M. Kaiser[1], P. Preiß[2], M. Weidemüller[1] and S. Jochim[1]

[1] *Physikalisches Institut, Heidelberg, Germany*
[2] *Max-Planck Institut of Quantum Optics, Garching, Germany*

The versatility and usability of quantum simulation using ultracold atoms is often limited by the amount of data collectable in a given time to achieve sufficiently good statistics. This is true in particular for measurements of phase diagrams or higher order correlations where many parameters are tuned simultaneously. In this new Lithium-6 experiment built at Heidelberg University this issue is addressed with the goal to reduce cycle times to below one second to make a step towards programmable quantum simulation.

In this contribution, I will give an overview of the already implemented features designed to enable high cycle rates, in particular the compact vacuum system including an octagonal, nano-texture coated glass cell, versatile magnetic field coils and a 0.66 NA objective. Further, I will give an outlook on other essential parts of the setup which are key to reduce cycle times, including an innovative optical dipole trap setup at 532 and 1064nm.

Compactifying the system using a 2D-MOT, a size of the vacuum apparatus comparable to a standard computer has been achieved. This compactification is also done for the optical setups around the science chamber, making the used optics modular exchangeable and small in size. From this we expect an increase in stability of the setup and higher fidelities, repeatability and debuggability.

Using single-atom free space imaging as well as in-situ measurement techniques, combined with high cycle rates, we aim to investigate in-situ and momentum correlations of various different physical systems, pathing a way towards programmable quantum simulation.

Observation of Anisotropic *Zitterbewegung* in Non-Abelian Gauge Field

M. Hasan[1,2], C. Madasu[2], K. Rathod[3], C. Kwong[2], C. Miniatura[3], F. Chevy[4], D. Wilkowski[2,3]

[1]University of Cambridge, Cavendish Laboratory, United Kingdom
[2] Nanyang Technological University,
School of Physical. and Mathematical Sciences, Singapore
[3]MajuLab, International Joint Research Unit IRL 3654,
CNRS, Université Côte d'Azur, Sorbonne Université, France
[4]Laboratoire de Physique de l'École normale supérieure, France

We experimentally observe *Zitterbewegung* in a two-dimensional degenerate Fermi gas, in the presence of a synthetic non-Abelian gauge field. Despite the fact that the original proposal of *Zitterbewegung*, by Schrodinger, did not have any requirement on the non-Abelian nature of the gauge field, we show that to observe anisotropic *Zitterbewegung*, the non-Abelian nature of the gauge field is an essential ingredient. In our experiments, we reveal the anisotropic nature of *Zitterbewegung*, namely, the direction-dependence of the oscillation-amplitude and the frequency of oscillation. To observe these effects, we leverage the momentum-dependence of the energy eigenstates, by introducing a kick to the atomic wave packet. Complete suppression of the *Zitterbewegung* is observed at special angles in momentum-space, and this phenomenon is understood with the spin texture of this spin-orbit coupled system. The role of Fermi degeneracy is manifested in the damping of the oscillation.

The Munich Lithium quantum microscope(s)

Sarah Hirthe[1,2], Dominik Bourgund[1,2], Petar Bojović[1,2],
Thomas Chalopin[1,2], Immanuel Bloch[1,2,3], and Timon A. Hilker[1,2]

[1] *Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[2] *Munich Center for Quantum Science and Technology, 80799 Munich, Germany and*
[3] *Fakultät für Physik, Ludwig-Maximilians-Universität, 80799 Munich, Germany*

In the last decade, quantum microscopes have been established as a versatile tool for quantum simulations by advancing both the imaging resolution and the local control to the scale of individual atoms.

In the Munich Lithium-6 setup, we developed a simultaneous single-site spin and density resolution to study exotic spin systems and doped antiferromagnets [1]. We use two 3D optical lattices; one high-power pinning lattice dedicated only to the high-resolution imaging step and a large-scale lattice for the Hubbard physics. Currently, we are upgrading the latter to a bichromatic superlattice with full control of the relative phase to implement novel cooling schemes and measurement bases.

I will present technical details of our microscope, including spin resolution, Raman sideband cooling, and shaping of the potential with a digital-mirror device. The new FermiQP project expands on these techniques by adding digital gates [2].

[1] See Poster of S. Hirthe
[2] See Poster of R. Groth

Towards fast, deterministic preparation of few-fermion states

M.Kaiser[1], T.Hammel[1], M.Bunjes[1], V.Leidel[1],

M.Weidemüller[1], P.M.Preiss[1,2] and S. Jochim[1]

[1]Physikalisches Institut - University of Heidelberg, Heidelberg, Germany
[2] Max Planck Institute of Quantum Optics, Garching, Germany

Measurements of higher-order correlations in quantum systems, e.g. for the tomography of complex quantum states, requires large data sets. This demand stands in contrast to typical cycle times of 10 seconds or more in traditional experiments with ultracold quantum gases.

We report on the ongoing development of an apparatus for fast, experimental quantum simulations using ultracold Lithium-6 with envisioned cycle times of well below 1 second. Within each run, few-fermion states are being prepared in a sequence based upon [1]. The resulting high data output will especially be key for iteration-intensive research in the future.

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Exploring Phase Diagrams of 1D Z_2 Lattice Gauge Theory with Dynamical Matter

<u>M. Kebrič</u>[1,2], U. Borla[2,3], S. Moroz[2,3,4], U. Schollwöck[1,2], L. Barbiero[5,6], and F. Grusdt[1,2]

[1]*Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, München D-80333, Germany*
[2]*Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany*
[3]*Physik-Department, Technische Universität München, 85748 Garching, Germany*
[4]*Department of Engineering and Physics, Karlstad University, Karlstad, Sweden*
[5]*ICFO-Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain*
[6]*Institute for Condensed Matter Physics and Complex Systems, DISAT, Politecnico di Torino, I-10129 Torino, Italy*

In this poster, we present a one-dimensional $\mathbb{Z}_2$ lattice gauge theory model where dynamical mater is coupled to gauge fields [1,2]. Such model exhibits confinement due to non-local interactions mediated by the gauge fields and can be realized with modern quantum simulators. In addition, we add nearest-neighbor interactions, which stabilize different Mott states at commensurate fillings of 1/2 and 2/3, thus uncovering rich phase diagrams which heavily depend on filling. These two Mott states are remarkably diverse. The Mott state for the 2/3 filling is stabilized by the nearest neighbor interaction and the confining $\mathbb{Z}_2$ electric field, thus indicating a Mott state of confined partons. On the other hand, the Mott state at 1/2 filling is stabilized by the nearest-neighbor interaction alone, indicating a Mott state of individual partons. We also consider adding superconducting terms instead of the nearest-neighbor interactions which results in trivial to non-trivial topological transitions, which resemble behavior of the Kitaev chain. In our work we rely on the combination of the numerical DMRG calculations and analytical techniques, which are tractable for specific parameter values and limits. We also develop an effective mean-field theory model of our problem, which correctly resembles the main features of the original model and offers deeper physical insights. Finally, we also discuss possible experimental realizations with quantum gases in optical lattices.

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Observation of a continuous time crystal

H. Keßler[1], P. Kongkhambut[1], J. Skulte[1], L. Mathey[1,2], J. G. Cosme[3], and A. Hemmerich[1,2]

[1]Zentrum für Optische Quantentechnologien and Institut für Laser-Physik, Universität Hamburg, 22761 Hamburg, Germany
[2]The Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany
[3]National Institute of Physics, University of the Philippines, Diliman, Quezon City 1101, Philippines

Time crystals are classified as discrete or continuous depending on whether they spontaneously break discrete or continuous time translation symmetry. While discrete time crystals have been extensively studied in periodically driven systems since their recent discovery, the experimental realisation of a continuous time crystal [1,2] is still pending. We report the observation of a limit cycle phase in a continuously pumped dissipative atom-cavity system [3], which is characterized by emergent oscillations in the intracavity photon number. We observe that the phase of this oscillation is random for different realisations, and hence this dynamical many-body state breaks continuous time translation symmetry spontaneously. The observed robustness of the limit cycles against temporal perturbations confirms the realisation of a continuous time crystal.

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Probing infinite many-body quantum systems with finite-size quantum simulators

Viacheslav Kuzmin[1,2], Torsten V. Zache[1,2], Christian Kokail[1,2], Lorenzo Pastori[1,2], Alessio Celi[1,2,3], Mikhail Baranov[1,2], and Peter Zoller[1,2],

[1] *Center for Quantum Physics, University of Innsbruck, Innsbruck A-6020, Austria*
[2] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck A-6020, Austria*
[3] *Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*

Experimental studies of synthetic quantum matter are necessarily restricted to approximate ground states prepared on finite-size quantum simulators. In general, this limits their reliability for strongly correlated systems, for instance, in the vicinity of a quantum phase transition (QPT). I present a protocol [1] that makes optimal use of a given finite-size simulator by directly preparing, on its bulk region, a mixed state representing the reduced density operator of the translation-invariant infinite-sized system of interest. This protocol is based on coherent evolution with a local deformation of the system Hamiltonian. For systems of free fermions in one and two spatial dimensions, the poster illustrates the underlying physics, which consists of quasi-particle transport towards the system's boundaries while retaining the bulk ``vacuum". For the example of a non-integrable extended Su-Schrieffer-Heeger model, it is demonstrated that the protocol enables a more accurate study of QPTs. In addition, I demonstrate the protocol for an interacting spinful Fermi-Hubbard model with doping for 1D chains where the initial state is a random superposition of energetically low-lying states.

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Sound Emission and Vortex Annihilation in a Superfluid Vortex Collider

Woo Jin Kwon[1]

[1]*CNR-INO, LENS, Sesto Fiorentino, Italy*

In quantum fluids, the quantized circulation of a vortex forbids the diffusion of a swirling flow observed in classical viscous fluids. Yet, moving vortices experience mutual friction due to interaction with a normal fluid, which causes energy dissipation of the superflow. Even in the absence of a normal fluid, the kinetic energy stored in the rotational flow can be dissipated into compressible sound energy when quantum vortices are accelerating, similar to the way an electric charge decelerates upon emitting electromagnetic waves. However, a deep understanding of the elementary mechanisms behind such irreversible vortex dynamics has been complicated by the scarcity of convincing experiments. We address this challenge by realizing a programmable, deterministic quantum vortex collider in a planar, homogeneous atomic fermionic superfluid. Engineering and monitoring the dynamics of vortex-antivortex pair and pair-pair collisions allow us to quantify the relaxation of the vortex energy due to sound emission and mutual friction. We directly visualize how the annihilation of two colliding vortex pairs radiates a density pulse in the superfluid. Further, we find a general tendency of stronger dissipation as we tune our system away from the bosonic regime into a superfluid of weakly bound fermion pairs, suggesting the essential roles played by fermionic quasiparticles localized inside the vortex core. Our experiment provides the first direct evidence of sound emissions from quantum vortex decay and non-universal dissipation features in distinct superfluid regimes.

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Adaptive Quantum State Tomography with Active Learning

H. Lange[1,2], **M. Kebric**[1,2], **M. Buser**[1,2], **F. Grusdt**[1,2] **and A. Bohrdt**[3,4]
[1]Department of Physics and Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München, München, Germany

[2]Munich Center for Quantum Science and Technology (MCQST), München, Germany

[3]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, USA
[4]Department of Physics, Harvard University, Cambridge, USA

Recently, tremendous progress has been made in the field of quantum science and technologies: different platforms for quantum simulation as well as quantum computing, ranging from superconducting qubits to neutral atoms in optical tweezers or lattices, are starting to reach unprecedentedly large systems. In order to benchmark these systems on the one hand, and gain physical insights on the other hand, the need for efficient tools to characterize quantum states arises.
The exponential growth of the Hilbert space with system size renders a full reconstruction of the quantum state prohibitively demanding in terms of necessary measurements. Most physically interesting states have some internal structure, which is however challenging to exploit without a priori physical knowledge about the system and thus a potential bias. Here, I will present the implementation of an efficient scheme for quantum state tomography using active learning. Based on a few initial measurements, the active learning protocol proposes the next measurement basis, designed to yield the maximum information gain. For a fixed total number of measurements and basis configurations, our algorithm thus maximizes the information one can obtain about the quantum state under consideration. The active learning quantum state tomography scheme is applied to reconstruct different multi-qubit states with varying degree of entanglement as well as to ground states of a kinetically constrained spin chain. In all cases, we obtain a significantly improved reconstruction as compared to a reconstruction based on the exact same number of measurements, but with randomly chosen basis configurations.
Our scheme is highly relevant to gain physical insights in quantum many-body systems, for example in quantum simulators, as well as for the characterization of quantum devices, and paves the way for benchmarking and probing large quantum systems.

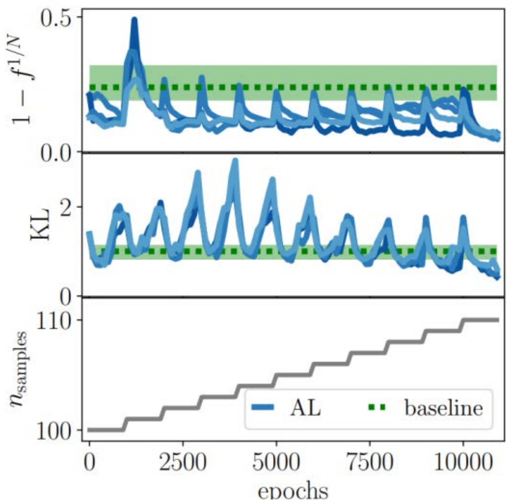

Figure 1 Learning curve: re-scaled fidelities (top), Kullback-Leibler divergence (middle) and number of samples (bottom) with active learning for a GHZ state with 9 qubits.

Thermal deconfinement in doped Z2 lattice gauge theories

S. Linsel[1,2], A. Bohrdt[3,4] and F. Grusdt[1,2]

[1]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany
[2]Ludwig-Maximilians University Munich, Munich, Germany
[3]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[4]Department of Physics, Harvard University, Cambridge, MA, USA
E-mail: Simon.Linsel@physik.uni-muenchen.de

Mobile charge carriers in high-Tc superconductors, i.e. holes doped into a Mott-insulator, leave behind a string of displaced spins when they move through the antiferromagnetic spin background. Here we study the thermal deconfinement of hole-pairs in a many-body setting using a classical 2D Z2 lattice gauge theory as a strongly simplified model of such strings. The confined phase is characterized by paired holes connected by (short) strings while deconfinement implies a global net of strings spanning over the entire lattice. Using classical Monte Carlo and percolation-inspired order parameters, we show that for very small hole-doping there is a thermal deconfinement phase transition with critical behavior. For larger hole-doping, we find strong indications that holes are always confined in the thermodynamic limit. Our results provide new insights into the physics of deconfinement of holes and can be tested experimentally using Rydberg-dressed quantum gases in optical lattices.

Observation of Josephson oscillations and superfluidity in a strongly correlated 2D Fermi gas

N. Luick[1,2], L. Sobirey[1,2], M. Bohlen[1,2,3], H. Biss[1,2], V.P. Singh[4,2], L. Mathey[4,2], T. Lompe[1,2], and H. Moritz[1,2]

[1]*Institut für Laserphysik, Universität Hamburg, Hamburg, Germany*
[2]*The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Hamburg, Germany*
[3]*Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France, Paris, France*
[4]*Zentrum für Optische Quantentechnologien, Universität Hamburg, Hamburg, Germany*

Strongly correlated 2D systems can give rise to superconductivity with high critical temperatures, but the origin for such unconventional superconductivity is still under debate. Ultracold 2D Fermi gases have emerged as clean and controllable model systems to study superfluidity in the presence of strong correlations and reduced dimensionality.

Here, we present our observation of phase coherence [1] and superfluidity [2] in an ultracold 2D Fermi gas.
We observe phase coherence by creating a tunnel junction in a homogeneous 2D Fermi gas and detecting Josephson oscillations between the weakly coupled reservoirs. We measure the frequency of such Josephson oscillations as a function of the phase difference across the junction and find excellent agreement with a sinusoidal current phase relation.
In a separate set of measurements, we observe superfluidity in a 2D Fermi gas by moving a periodic potential through the system and detecting no dissipation below a critical velocity v_c. We measure v_c as a function of interaction strength and find that the gas is superfluid throughout the entire BEC-BCS crossover.

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Mesoscopic Fermion systems in rotating traps

P. Lunt[1], P. Hill[1], S. Jochim[1], P. Preiss[1]

[1] *Physikalisches Institut, Heidelberg, Germany*
E-mail: lunt@physi.uni-heidelberg.de

The equivalence of charged particles in external magnetic fields and neutral atoms in rapidly rotating traps opens up new avenues to study quantum hall physics with ultracold atomic gases.
In order to access the microscopic level of strongly correlated states we build on our previously established experimental methods – the deterministic preparation of ultracold 6Li few Fermion systems in low dimensions [1,2], as well as local observation of their correlation and entanglement properties on the single atom level [3].
Here, we present current experimental progress towards adiabatic preparation of deterministic mesoscopic Fermion systems in rapidly rotating optical potentials. We showcase the optical setup, in particular the generation of interfering a Gaussian and Laguerre-Gaussian mode to achieve rotation [4]. Moreover, we show first experimental results of the new setup.

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Spin and density self-ordering in dynamic polarization gradients fields

N. Masalaeva[1,2], W. Niedenzu[2], F. Mivehvar[2], and H. Ritsch[2]

[1]Saint Petersburg State University, Saint Petersburg, Russia
[2]Institut für Theoretische Physik, Universität Innsbruck, Innsbruck

In our work [1] we study the zero-temperature quantum phase diagram for a two-component Bose-Einstein condensate in an optical cavity. The two atomic spin states are Raman coupled by two transverse orthogonally polarized, blue-detuned plane-wave lasers inducing a repulsive cavity potential. For a weak pump the lasers favor a state with homogeneous density and predefined uniform spin direction. When one pump laser is polarized parallel to the cavity mode polarization, the photons coherently scattered into the resonator induce a polarization gradient along the cavity axis, which mediates long-range density-density, spin-density, and spin-spin interactions. We show that the coupled atom-cavity system implements central aspects of the t-J-V-W model with a rich phase diagram. At the mean-field limit we identify at least four qualitatively distinct density- and spin-ordered phases including ferromagnetic and antiferromagnetic order along the cavity axis, which can be controlled via the pump strength and detuning. Real-time observation of amplitude and phase of the emitted fields bears strong signatures of the realized phase and allows for real-time determination of phase transition lines. Together with measurements of the population imbalance, most properties of the phase diagram can be reconstructed.

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Confinement of Dynamical Charges in Z_n Lattice Gauge Theory

Conall Vincent McCabe[1,2] , **Matjaž Kebrič**[1,2], **Fabian Grusdt**[1,2]

[1]Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany
[2] Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany

Recently there has been a renewed interest in Lattice Gauge Theories (LGT) amongst the condensed matter community , in large part due to offering an ideal testing bed for quantum simulation ,which can give more insight into challenging problems such as the nature of transitions from confined to deconfined charges.
The phenomenon of confinement manifests itself in a linear potential between two static charges when matter couples to gauge fields. However when such charges become dynamical, understanding confinement becomes a difficult task.
Recent work has shown that the confinement transition in a class of 1D Z_2 LGT of bosons interacting locally can be related to the breaking of a certain translation symmetry in a non-local basis [1] . We investigate to what extent this equivalence generalises to a more exotic model, namely the discretised Schwinger model, a model for QED in (1 + 1) dimensions.
Protocols have been proposed and realised to quantum simulate such a model in trapped atom experiments [2,3]. We investigate snapshot-based characterisations of the confinement transition in this new string basis which could be accessible in such experiments.

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Vortices in rotating Bose gas interacting via finite range Gaussian potential in a quasi-two-dimensional harmonic trap

Md Hamid[1,*] and M. A. H. Ahsan[1,†]

[1] *Department of Physics, Jamia Millia Islamia (A Central University), New Delhi 110025, India*

(Dated: March 9, 2022)

A system of harmonically trapped N=16 spin-0 bosons confined in quasi-2D symmetrical $x-y$ plane interacting via a finite range repulsive Gaussian potential is studied under an externally impressed rotation to an over all angular velocity Ω about the $z-$axis. The exact diagonalization (ED) of $n \times n$ many-body Hamiltonian matrix in a given subspace of quantized total angular momentum $0 \leq L_z \leq 4N$ is performed using Davidson algorithm[1]. For $N = 16$and $L_z = 32$, the dimensionality of the Hilbert space turns out to be $n = 384559$. With increase in the interaction range in the Gaussian potential, the active Fock space size gets reduced and hence computation becomes more feasible compared to the zero-range δ-function potential. Following this idea, we considered the interaction-range parameter $\sigma = 0.30, 0.50$ and 0.75 to study the finite-range effects on the many-body ground state. The trap velocity Ω being the Langrange multiplier associated with the angular momentum L_z for the rotating systems, the $L_z - \Omega$ phase diagram (or stability line) is drawn which determines the critical angular velocities, $\Omega_{\mathbf{c_i}}, i =, 0, 1, 2..$, at which, for a given angular momentum L_z, the system goes through a quantum phase transition. There is an increase in the critical angular velocity ($\Omega_{\mathbf{c}_i}$, $i = 1, 2, 3...$) and in the largest condensate fraction λ_1 calculated using single particle reduced density matrix eigen-values with increase in the interaction range σ. We calculated the von-Neumann quantum entropy (S_1), degree of condensation (C_d) and the conditional probability density (CPDs). There is no significant change in von-Neumann entropy S_1 and the degree of condensation C_d in slow-rotating gas in the region $0 \leq L_z \leq (L_z = N)$. However, for higher angular momentum, $L_z \geq 2N$, with increase in interaction range σ, small variations in S_1 and C_d are observed. We plot the isosurface CPDs plots for conditional probability and hence study the nucleation of vortex states, which is one of the signature of rotating bose gas, we report that with the increase in interaction range σ, the probility density starts accumulation at the edge of vortices. Accumulation of density at the surfaces of sphere in the case of Bose-condensate in the bubble trap has been discussed here [2]. We also observed that the vortices entry statred for the higher σ followed by the lower. We ploted the CPDs to study $p = 1, 2, 3, 4, 5$ fold symmetrical vortex lattices. Concluding we suggest the modification of single particles basis state with the increase in σ at $L_z = 32$, $\sum_{i=1,3}(n_i, m_i)(\sigma = 0.30)$ $[(2, 2), (0, 0), (4, 4)]$, $\sum_{i=1,3}(n_i, m_i)(\sigma = 0.50)$ $[(2, 2), (0, 0), (4, 4)]$ and $\sum_{i=1,3}(n_i, m_i)(\sigma = 0.75)$ $[(2, 2), (3, 3), (1, 1)]$.

L_z	$\lambda_1(\sigma = 0.30)$	$\lambda_1(\sigma = 0.50)$	$\lambda_1(\sigma = 0.75)$
0	0.989	0.993	0.997
16	0.875	0.879	0.883
32	0.435	0.481	0.639
48	0.484	0.479	0.468
60	0.493	0.501	0.505

In the Table adjecent, the condensate fraction λ_1 increases with icrease in the interaction range σ and the deplates with increase in the L_z.

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* hamid160520@st.jmi.ac.in

† mahsan@jmi.ac.in

Quantized transport of solitons in nonlinear Thouless pumps

N. Mostaan[1,2,3] and F. Grusdt[1,2] and N. Goldman[3]

[1] Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 München, Germany

[2] Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany

[3] CENOLI, Université Libre de Bruxelles, CP 231, Campus Plaine, B-1050 Brussels, Belgium

The investigation of topological effects in nonlinear synthetic systems has led to the discovery of remarkable phenomena such as topologically quantized transport of solitons [1], where a soliton bifurcating from a topological band undergoes Thouless pumping according to the Chern number of the band. Such phenomena necessitate an extension of notions in topological physics of linear systems to the realm of nonlinear systems [2], a non-trivial task due to the lack of a unified theoretical framework. Here we investigate the bright solitons of the paradigmatic nonlinear Schrödinger equation, where the Hamiltonian dynamics exhibits Thouless pumping. While the topological transport of such solitons has been experimentally demonstrated in photonic waveguide arrays, a theoretical understanding of the underlying mechanism is still lacking. By representing the equations of motion in terms of Wannier functions, we obtain an effective model describing the soliton evolution during the pump sequence, which enables us to prove the quantized displacement of the soliton by the Chern number of the topological band. We discuss the possible realization of soliton topological pumping in one-dimensional ultracold gases. In particular, we demonstrate that two-component mixtures of bosonic particles can realize interesting interaction-induced topological effects, where minority species loaded in a topologically trivial lattice experience quantized displacement upon interaction with majority particles undergoing a Thouless pump sequence. This phenomenon is another instance of the interplay of topology and interaction-induced nonlinearities.

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Quantum Information in Assembled Optical Lattice Systems

Naman Jain and Philipp Preiss

Max Planck institute of Quantum Optics, Garching, Germany

Cold atoms in optical lattices are an experimental system right at the interface of condensed matter physics and quantum optics: On the one hand, they naturally realize Hamiltonians known from the solid state such as the Hubbard model or fermionic superfluids. On the other hand, they are amenable to single-particle control usually found in few-mode systems and offer the opportunity to study many-body physics with qualitatively new observables and correlation functions. This combination opens the door for experimental schemes that combine ideas from quantum information and condensed matter physics.

Our group will focus on novel approaches to measuring global properties of the density matrix of many-body systems. This approach may serve, for example, to characterize out-of-equilibrium systems through their entanglement dynamics. A major bottleneck in measuring such quantities has been the requirement for extremely large statistics. We will tackle this problem through new techniques for the rapid assembly of optical lattice systems from individually prepared atoms.

Quantum probes for many-body systems

M. Prüfer[1], T. V. Zache[2,3], T. Zhang[1], M. Tajik[1], P. Zoller[2,3] and J. Schmiedmayer[1]

[1] *Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, Vienna, Austria*
[2] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck A-6020, Austria*
[3] *Center for Quantum Physics, University of Innsbruck, Innsbruck A-6020, Austria*

The key ingredient for understanding many-body systems when performing quantum simulations is an efficient readout of the available information. In quantum systems every extraction of information implies a backaction altering the system's state. Here, we present the first steps towards new quantum-limited probes for many-body quantum systems. For our experimental studies we use one-dimensional Bose-Einstein condensates on an atomchip combined with spatially resolved measurements.

To probe the system, we employ global as well as local fields for outcoupling a controllable number of atoms which we detect with near unit efficiency. The controlled outcoupling allows us to tune the strength of the perturbation and we thus can study the influence of the measurement backaction.

We further present a new approach to Hamiltonian learning for many-body systems. Translating the recently developed methods for discrete systems to the framework of quantum fields, we aim to study the scale dependence of the emerging physics. We present first results in the regime of a quadratic Hamiltonian and give an outlook on the possibilities for more complex situations.

Robust stripes in the mixed dimensional t-J model

Henning Schlömer[1,2], **Annabelle Bohrdt**[3], **Ulrich Schollwöck**[1,2], **Lode Pollet**[1,2], **and Fabian Grusdt**[1,2]

[1] *Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstr. 37, München D-80333, Germany*

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

[3] *Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany*

We analyze stripe formation in the doped mixed-dimensional (mixD) variant of the t-J model, where charge carriers are restricted to move only in one direction, whereas magnetic interactions are two-dimensional. Using the density matrix renormalization group, we find a stable stripe phase with inhomogeneous order in the mixD setting, featuring incommensurate magnetic order and oscillating hole density profiles in the hopping direction over the whole range of the simulated system size. We estimate critical temperatures as a function of hole doping below which stripes with incommensurate magnetic order are observable on the length scale of the considered system. We find that critical temperatures are of the order of the magnetic coupling J, hence being within reach with current state-of-the-art ultracold quantum simulators.

Generation of massively entangled optical states

P. Stammer[1], J. Rivera-Dean[1], Th. Lamprou[2], E. Pisanty[3], MF. Ciappina[4], P. Tzallas[2] and M. Lewenstein[1,5]

[1]*ICFO, Barcelona, Spain*
[2] *FORTH, Heraklion (Crete), Greece*
[3] *King's College London, London, United Kingdom*
[4] *Guangdong Technion, Guangdong, China*
[5] *ICREA, Barcelona, Spain*

We theoretically propose a novel scheme to generate massively entangled optical states by using the interaction of intense laser fields with atoms [1]. Using a recently developed quantum optical description of the process of high harmonic generation [2], we can show that all the field modes participating in the process are entangled [1,3]. Due to the high degree of coherent control of the underlying electron dynamics the properties of the massively entangled states allows to tailor entangled single photon states, as well as entangled coherent states orders of magnitude higher than those provided by current technology. Furthermore, we have experimentally demonstrated that a conditioning procedure on some of the field modes leads to high photon number (<n> = 9) optical Schrödinger cat states [4]. This scheme allows to conceive a new class of light engineering protocols covering a photon number range over several orders of magnitude, and field mode frequencies from the far-IR to the XUV regime [3].

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Distinguishing Cavity Induced Transparency from Autler-Townes Splitting using Exceptional Points

A. P. Synanidis[1], A. F. Terzis[2] and E. Paspalakis[1]

[1]Materials Science Department, School of Natural Sciences, University of Patras, 26504 Patras, Greece

[2] Department of Physics, School of Natural Sciences, University of Patras, 265 04 Patras, Greece

Email: adamsynanidis@gmail.com

In the field of Quantum Microscopy, two interesting phenomena that concern the optical properties of quantum systems are the cavity induced transparency (CIT) [1] and the Autler-Townes splitting (ATS) [2], but distinguishing between the two is still a challenge. Here, we address the above problem by considering a two-level quantum system interacting with a weak probe field and placed in a single optical cavity, where we find both CIT and ATS take place with slow group velocity for the probe field. We develop a systematic way of distinguishing between the two, using the Exceptional Point (EP)[3] of the effective non-Hermitian Hamiltonian that describes the open quantum system. We show that the phase transition from CIT to ATS takes place at the region of the EP.

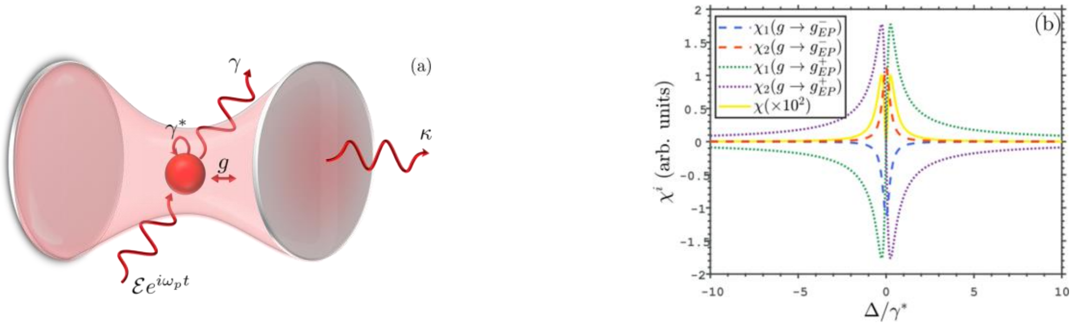

Figure 1: (a) Schematic of the system. A Quantum Emitter with spontaneous decay rate *(γ)* and pure dephasing *(γ*)*, is coupled with strength *(g)* to the electromagnetic mode of an optical cavity with decay rate *(κ)* and is interacting with an external probe field of amplitude *(E)* and frequency *(ω_p)*. **(b)** The "free-QEs" and the total system's susceptibility *(χ_1, χ_2 and χ)* as a function of detuning $\Delta=\omega_p-\omega_{QE}$, for various values of *g*. The phase transition from CIT *($g<g_{EP}$)* to ATS *($g>g_{EP}$)* is evident by the drastic change of the equivalent "free-QE" susceptibilities of the system around the Exceptional Point.

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Adiabatic charge pumping in bosonic Chern-insulator analogs

Isaac Tesfaye[1], Botao Wang[1], André Eckardt[1]

[1]IInstitut für Theoretische Physik, Technische Universität Berlin,
Hardenbergstraße 36, 10623 Berlin, Germany
Email: i.tesfaye@tu-berlin.de

Mimicking fermionic Chern insulators with bosons has drawn a lot of interest in experiments by using, for example, cold atoms [1,2] or photons [3].
Here we present a scheme to prepare and probe a bosonic Chern insulator analog by using an ensemble of randomized bosonic states.
By applying a staggered superlattice, we identify the lowest band with individual lattice sites. The delocalization over this band in quasi-momentum space is then achieved by introducing on-site disorder or local random phases.
Adiabatically turning off the superlattice then gives rise to a bosonic Chen insulator, whose topologically non-trivial property is further confirmed from the Laughlin-type quantized charge pumping.
Our protocol may provide a useful tool to realize and probe topological states of matter in quantum gases or photonic waveguides.

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Liouvillian Skin Effect in an Exactly Solvable Model

F. Yang[1], Q-D. Jiang[1,2] and E. J. Bergholtz[1]

[1]*Department of Physics, Stockholm University, AlbaNova University Center, Stockholm, Sweden*

[2] *Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China*

The interplay between dissipation, topology and sensitivity to boundary conditions has recently attracted tremendous amounts of attention at the level of effective non-Hermitian descriptions. Here we exactly solve a quantum mechanical Lindblad master equation describing a dissipative topological Su-Schrieffer-Heeger (SSH) chain of fermions for both open and periodic boundary conditions [1]. We find that the extreme sensitivity on the boundary conditions associated with the non-Hermitian skin effect is directly reflected in the rapidities governing the time evolution of the density matrix giving rise to a Liouvillian Skin Effect [2,3]. This leads to several intriguing phenomena including boundary sensitive damping behavior, steady state currents in finite periodic systems, and diverging relaxation times in the limit of large systems. We illuminate how the role of topology in these systems differ in the effective non-Hermitian Hamiltonian limit and the full master equation framework.

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Tunable transport in the mass-imbalanced Fermi-Hubbard model

Philip Zechmann[1,2], Alvise Bastianello[1,2], Michael Knap[1,2]

[1]Department of Physics, Technical University of Munich, 85748 Garching, Germany
[2] Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 München, Germany

Relaxation of a non-equilibrium quantum state towards a thermal equilibrium takes place on different time and length scales. In presence of conserved quantities the slowest part is the transport of conserved charges, which is accurately described by the classical laws of hydrodynamics. However, for systems with dynamical constraints, such as two component mixtures with very different single-particle mobilities, reaching the hydrodynamic regime may potentially take a long time, leading to an unconventionally slow equilibration. We study relaxation dynamics and transport in the one-dimensional Fermi-Hubbard model with unequal masses within quantum Boltzmann theory. For strong mass imbalance we find an extended regime of slow dynamics, where the slow species impedes the transport of the fast one significantly. At late times the Boltzmann theory predicts coupled diffusive hydrodynamics, and we calculate the diffusion matrix as a function of the mass-ratio and temperature. We numerically solve the inhomogeneous Boltzmann equation and compare our results to tensor network simulation, where we find excellent agreement in a wide parameter range, and assess the limitations of the kinetic theory for strong interactions and large mass imbalance. Additionally, recent experimental results, where the mass-imbalanced Fermi-Hubbard model is implemented with ultracold Ytterbium atoms [1], show qualitative agreement with our results.

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