Ultracold Quantum Matter: Basic Research and Applications

777. WE-Heraeus-Seminar

12 Dec - 16 Dec 2022
at the Physikzentrum Bad Honnef/Germany

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

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

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 777. WE-Heraeus-Seminar:

Since the first experimental realization of Bose-Einstein condensation in ultracold atomic gases in 1995, there have been several substantial breakthroughs. Today, systems of bosonic or fermionic quantum gases allow for a very high level of experimental control concerning all ingredients of the underlying many-body Hamiltonian. Therefore, ultracold atomic or molecular quantum gases are considered to be ideal quantum simulators, that is, they are best capable to simulate difficult problems in quantum many-body physics as they occur in condensed matter physics and other fields of physics.
In response to the occurrence of many new research directions in recent years, it is highly desirable to give a coherent overview over the diverse facets which are now appearing, and to reflect upon the future perspectives of the field. Thus, the seminar follows the interdisciplinary concept in bringing together experimental and theoretical scientists, who investigate the properties of ultracold quantum gases from different points of view, to exchange opinions, discuss problems, and disseminate new ideas. On the one hand, invited plenary talks by 25 selected leading international experts will guarantee a high scientific level for the seminar, and will provide its main backbone. On the other hand, all other participants will be given the opportunity to present their current research work within a high-class setting through shorter contributed talks or through posters, thereby generating a forum for identifying the most promising current trends and future perspectives.

Scientific Organizers:

PD Dr. Axel Pelster — Technische Universität Kaiserslautern, Germany
E-mail: axel.pelster@physik.uni-kl.de

Prof. Dr. Carlos Sá de Melo — Georgia Institute of Technology, Atlanta, USA
E-mail: carlos.sademelo@physics.gatech.edu

Introduction

Administrative Organization:

Dr. Stefan Jorda
Martina Albert

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

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

Venue:

Physikzentrum
Hauptstrasse 5
53604 Bad Honnef, Germany

Conference Phone +49 2224 9010-120

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

Taxi Phone +49 2224 2222

Registration:

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

Program

Ultracold Quantum Matter: Basic Research and Applications

777. WE-Heraeus-Seminar

12 Dec - 16 Dec 2022
at the Physikzentrum Bad Honnef/Germany

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

WILHELM UND ELSE HERAEUS-STIFTUNG

Program

Sunday, 11 December 2022

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

Monday, 12 December 2022

07:30 – 08:40	*BREAKFAST*	
08:40 – 09:00	Carlos Sá de Melo	**Opening and Welcome**

Session 1: Ultracold Atoms in Space

09:00 – 09:45	Nathan Lundblad	**Studying ultracold bubbles in orbital microgravity with the NASA Cold Atom Laboratory**

Session 2: Fermi Gases

09:45 – 10:30	Nir Navon	**Fermions in an optical box**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Chris Vale	**Higgs mode in strongly interacting Fermi gases**
11:45 – 12:30	Yvan Castin	**Collective (Higgs) excitation branch in the broken pair continuum of pair-condensed spin 1/2 Fermi gases**
12:30 – 14:00	*LUNCH*	

Program

Monday, 12 December 2022

Session 3: Contributed Talks I

14:00 – 14:30	Hauke Biss	**Excitation spectrum and superfluid gap of an ultracold Fermi gas**
14:30 – 15:00	Anne-Maria Visuri	**Superfluid transport through a dissipative quantum point contact**
15:00 – 15:30	Kali Wilson	**Using vortices as probes of quantum many-body systems**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 18:30	**Plenary Poster Flash Presentations**	
18:30 – 20:00	*DINNER*	
20:00 – 22:00	**Poster Session I**	

Program

Tuesday, 13 December 2022

08:00 – 09:00	*BREAKFAST*	

Session 4: Spin Physics

09:00 – 09:45	Dieter Jaksch	**Quantum physics in connected worlds**
09:45 – 10:30	Tilman Enss	**Polaron interaction in superfluids**
10:30 – 10:35	***Conference Photo***	
10:35 – 11:00	*COFFEE BREAK*	

Session 5: Open Quantum Systems

11:00 – 11:45	Herwig Ott	**Ultracold Bose gases in driven-dissipative environments**
11:45 – 12:30	Achim Rosch	**Dicke transition in open many-body systems determined by fluctuation effects**
12:30 – 14:00	*LUNCH*	

Session 6: Indistinguishability

14:00 – 14:45	Niels Kjaergaard	**Effects of quantum mechanical identity in scattering of atoms and light**
14:45 – 15:30	Kazimierz Rzążewski	**The Fock states sampling method**
15:30 – 15:45	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
15:45 – 16:15	*COFFEE BREAK*	
16:15 – 18:45	**Poster Session II**	
18:45 – 20:00	*HERAEUS DINNER at the Physikzentrum (cold and warm buffet, with complimentary drinks)*	
20:00 – 22:00	**2022 FIFA World Cup: Semifinal I**	

Program

Wednesday, 14 December 2022

08:00 – 09:00	*BREAKFAST*	

Session 7: Quantum Droplets and Supersolidity

09:00 – 09:45	Lauriane Chomaz	**Many-body physics with quantum gases of magnetic lanthanide atoms: advances and new trends**
09:45 – 10:30	Tim Langen	**Supersolidity in dipolar Bose-Einstein condensates**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Blair Blakie	**Crystallisation transition of a dipolar Bose gas in an infinite tube**
11:45 – 12:30	Leticia Tarruell	**Unconventional superfluids in quantum gases with competing interactions**
12:30 – 14:00	*LUNCH*	
14:00 – 16:30	**Excursion** **Walk**	
16:30 – 18:00	**Wine Tasting at Vinery Broel**	
18:30 – 20:00	*DINNER*	
20:00 – 22:00	**2022 FIFA World Cup: Semifinal II**	

Program

Thursday, 15 December 2022

08:00 – 09:00	*BREAKFAST*	

Session 8: Quantum Dynamics

09:00 – 09:45	Tanja Mehlstäubler	**Non-equilibrium dynamics and nanofriction in ion Coulomb crystals**
09:45 – 10:30	Michael Knap	**Characterizing sine-Gordon dynamics with quantum gas microscopes**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Ian Spielman	**Topology in time-evolving quantum systems**
11:45 – 12:30	Cheng Chin	**Many-body chemistry - reactions of quantum degenerate molecules**
12:30 – 14:00	*LUNCH*	

Session 9: Lattice Systems

14:00 – 14:45	Ana Maria Rey	**Quantum simulation with spin-orbit-coupled fermions in optical lattices**
14:45 – 15:30	Fabrice Gerbier	**Anomalous loss of coherence of strongly interacting bosons in optical lattices**
15:30 – 16:15	Walter Hofstetter	**Correlated topological quantum states in ultracold atoms**
16:15 – 17:00	*COFFEE BREAK*	

Program

Thursday, 15 December 2022

Session 10: Contributed Talks II

17:00 – 17:30	David Clément	**Full counting statistics of interacting lattice gases after an expansion: role of the condensate depletion on the many-body coherence**
17:30 – 18:00	Jan Arlt	**Microcanonical Fluctuations in a Bose-Einstein Condensate and its thermal cloud**
18:00 – 18:30	Manfred Mark	**Supersolidity, Bloch oscillations and vortices in dipolar quantum gases**
18:30 – 20:00	*DINNER*	
20:00 – 22:00	**Free Discussion**	

Posters

Posters I

01	Karima Abbas (online)	**Binary Bose–Einstein condensates in a disordered time-dependent potential**
02	Ragheed Alhyder	**Impurities as probes for quantum phase transition**
03	Usman Ali	**Super Bloch oscillations with a parametrically modulated parabolic trap**
04	Antun Balaž	**Stability of quantum degenerate fermionic polar molecules with and without microwave shielding**
05	Paramjeet Banger (online)	**Effective potentials in rotating spin-orbit coupled BECs**
06	André Becker	**Pseudo Jahn-Teller Effect in one-dimensional confined fermions**
07	Rita Behera Sahoo (online)	**Understanding quantum assisted optical activity by narrow band frequency comb using Trichromatic field model**
08	Stefan Birnkammer	**Prethermalization in one-dimensional quantum many-body systems with confinement**
09	Russell Bisset	**2D supersolid formation in dipolar condensates**
10	Thomas Bland	**Alternating-domain supersolids in binary dipolar condensates**
11	Patrick Boegel	**Matter-wave lensing of shell-shaped Bose-Einstein condensates**
12	Martin Bonkhoff	**Statistically Suppressed Coherence in the Anyon-Hubbard Dimer**
13	Abdelaali Boudjemaa (online)	**Self-bound liquid droplets in a Gaussian-correlated disorder potential**

Posters I

14	Justus Brüggenjürgen	**Search for anyonic quasi-particles in a lithium matter-wave microscope**
15	Renan da Silva Souza	**Emergence of damped-localized excitations of the Mott state due to disorder**
16	Piotr Deuar	**Survival of the quantum depletion of a condensate after release from its trap**
17	Julian Feß	**Dynamical phase transition in an open quantum system**
18	Arnaldo Gammal	**Stability of a Bose-condensed mixture on a bubble trap**
19	Weronika Golletz	**N Impenetrable Particles Bouncing on a Mirror: Discrete Time Crystals**
20	Edvinas Gvozdiovas	**Interference Induced Anisotropy in 2D Optical Lattices**
21	Soumyadeep Halder	**Two-dimensional miscible-immiscible supersolid and droplet crystal state in a homonuclear dipolar bosonic mixture**
22	Elmar Haller	**Instabilities of interacting matter waves in optical lattices with periodic driving.**
23	René Henke	**Ultracold Fermi Gases in Box Potentials**
24	Edward Iraita Salcedo	**Quantum gases research out of equilibrium-quench**
25	Hans Keßler	**Dissipative time crystals in an atom-cavity platform**
26	Wyatt Kirkby	**Binary supersolids in antidipolar mixtures**

Posters II

27	Jan Arlt	**Microcanonical Fluctuations in a Bose-Einstein Condensate and its thermal cloud**
28	Georgios Koutentakis	**Magnetic processes in Bose Einstein condensates coupled to impurities: state-dressing and Magnetic polarons**
29	Arthur La Rooij	**Controllable commensurate to incommensurate filling of weakly interacting bosons in 1D**
30	Felix Lang	**Tunable diffusion properties of spin-polarized Fermi gases in time-dependent disorder**
31	Dwipesh Majumder	**Collective excitations in quantum droplets of Bose-Bose mixture**
32	Andreas Morgen	**Impurity physics with Bose-Einstein condensates**
33	Kristian Knakkergaard Nielsen	**Nonequilibrium hole dynamics in antiferromagnets: damped strings and polarons**
34	Maitri Pathak (online)	**Pattern formation on quantum droplet in the presence of quasi-periodic optical lattice**
35	Axel Pelster	**Quantum mechanical description of thermo-optic interaction in photon BECs**
36	Maciej Pieczarka	**Thermalization of photons in InGaAs/GaAs quantum wells and optically pumped VCSELs**
37	Milan Radonjić	**Out of equilibrium dynamical properties of Bose-Einstein condensates in ramped up weak disorder**

Posters II

38	David Reinhardt	**Conformal Duality of Bose-Einstein condensates with two- and three-body interactions**
39	Rhombik Roy (online)	**Probing relaxation dynamics of few strongly correlated bosons in 1D triple well optical lattice**
40	Natália Salomé Móller	**Bose-Einstein condensation on Curved Manifolds**
41	Marija Šindik	**Creation and robustness of quantized vortices in a dipolar supersolid when crossing the superfluid-to-supersolid transition**
42	Jim Skulte	**Dynamical phases in an atom-cavity system: From time crystals to dark states**
43	Justyna Stefaniak	**Self-oscillating pump in a topological dissipative atom–cavity system**
44	Philipp Stürmer	**Mixed Bubbles in a one-dimensional Bose-Bose mixture**
45	Sumaita Sultana	**Josephson-type oscillation in a spin-orbit coupled Bose-Einstein Condensate in the presence of nonlinear optical lattices**
46	Mohsen Talebi	**Particle and heat transport of a unitary fermi gas through a dissipative quantum point contact**
47	Lauro Tomio	**Vortex flow and quantum turbulence generated in stirred mass-imbalanced Bose-Einstein condensed mixtures**
48	Andrea Tononi	**Self-bound fermionic mixtures in 1D**
49	Buğra Tüzemen	**Excitations of a dipolar Tonks-Girardeau droplet**

Posters II

50	Artem Volosniev	**Dissipative dynamics of an impurity with spin-orbit coupling**
51	Jiachen Zhao	**QRydDemo - A Rydberg Atom Quantum Computer Demonstrator**
52	Yong-Guang Zheng (online)	**Approaching practical quantum computational advantage using ultracold atoms**
53	Tianwei Zhou	**Universal Hall response and flavour-selective localization in strongly interacting lattice fermions**

Abstracts of Lectures

(in alphabetical order)

Microcanonical Fluctuations in a Bose-Einstein condensate and its thermal cloud

T. Vibel[1], K. Pawłowski[2], K. Rzążewski[2], M. A. Kristensen[1], J. J. Arlt[1]

[1]*Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C*

[2]*Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02-668 Warsaw*

Quantum systems are typically characterized by the inherent fluctuation of their physical observables. Here we report the characterization of atom number fluctuations in weakly interacting Bose-Einstein condensates. Technical fluctuations are mitigated through a combination of non-destructive detection and active stabilization of the cooling sequence. We observe fluctuations reduced by 27% below the canonical expectation for a non-interacting gas, revealing the microcanonical nature of our system [1]. Similar fluctuations are observed in the thermal cloud, which are closely correlated to the BEC results. This confirms the nature of the fluctuations between the two components of the system. Our experimental results thus set a benchmark for theoretical calculations under typical experimental conditions [2].

References

[1] M. B. Christensen et al., Phys. Rev. Lett. **126**, 153601 (2021)
[2] M. B. Kruk et al., arXiv:2207.04536

Excitation Spectrum and Superfluid Gap of an Ultracold Fermi Gas

H. Biss[1,2], L. Sobirey[1], N. Luick[1,2], M. Bohlen[1,2], J. J. Kinnunen[3], G. M. Bruun[4,5], T. Lompe[1,2], and H. Moritz[1,2]

[1]*Institute of Laser Physics, University of Hamburg, Hamburg, Germany*
[2]*The Hamburg Centre for Ultrafast Imaging, University of Hamburg, Hamburg, Germany*
[3]*Department of Applied Physics, Aalto University School of Science, Aalto, Finland*
[4]*Center of Complex Quantum Systems, Department of Physics and Astronomy, Aarhus University, Denmark*
[5]*Shenzen Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology, Shenzhen, China*

Ultracold Fermi gases with tunable interactions have allowed realizing the famous BEC-BCS crossover from a Bose-Einstein condensate (BEC) of molecules to a Bardeen-Cooper-Schrieffer (BCS) superfluid of weakly bound Cooper pairs [1,2]. However, large parts of the excitation spectrum of fermionic superfluids in the BEC-BCS crossover are still unexplored.

In this contribution, I would like to present, how we use Bragg spectroscopy [3] to measure the full momentum-resolved low-energy excitation spectrum of strongly interacting ultracold Fermi gases.

This enables us to observe the smooth transformation from a bosonic to a fermionic superfluid in the BEC-BCS crossover. We also use our spectra to determine the evolution of the superfluid gap and find excellent agreement with previous experiments [4,5] and self-consistent T-matrix calculations [6] both in the BEC and crossover regime. However, towards the BCS regime, a calculation that includes the effects of particle-hole correlations [7] shows better agreement with our data.

In addition to the work mentioned above [8], I would like to give an overview of our current progress towards spin-imbalanced 2D Fermi gases [9-14] in box potentials.

References

[1] M. Bartenstein et al., PRL **92**, 120401 (2004),
[2] C. A. Regal et al., PRL **92**, 120403 (2004)
[3] M. G. Lingham et al., J. Mod. Opt. **63**, 1783-1794 (2016)
[4] A. Schirotzek et al., PRL **101**, 140403 (2008)
[5] S. Hoinka et a.l, Nat. Phys. **13**, 943 (2017)
[6] R. Haussmann et al., PRA **74**, 023610 (2007)
[7] L. Pisani, PRB **98**, 104507 (2018)
[8] H. Biss et al., PRL **128**, 100401 (2022)
[9] M. W. Zwierlein et al., Science **311**, 492-496 (2006)
[10] Y. Shin et al., Nature **451**, 689-693 (2008)
[11] N. Navon et al., Science **328**, 729-732 (2010)
[12] Y.-A. Liao et al., Nature **467**, 567-569 (2010)
[13] W. Ong et al., PRL **114**, 110403 (2015)
[14] D. Mitra et al., PRL **117**, 093601 (2016)

Crystallisation transition of a dipolar Bose gas in an infinite tube

P. Blair Blakie, **Joseph Smith**, **Danny Baillie**

[1] *Dodd-Walls Centre for Photonic and Quantum Technologies, New Zealand and Department of Physics, University of Otago, Dunedin 9016, New Zealand*

We present a theory for the emergence of a crystalline and potentially supersolid state of a dipolar quantum Bose gas confined to an infinite tube potential. This system is an idealization of the cigar shaped dipolar Bose gases that have been successfully used in experiments to prepare supersolids. We present results for the system phase diagram as a function of the average linear density of the gas. Our results are based on a direct numerical solution and a simpler reduced three-dimensional theory, where the condensate wave function is decomposed into an axial field and a transverse part described variationally. We find that the supersolid transition has continuous and discontinuous regions as the averaged density varies. The continuous transition is connected with the softening of a roton-like excitation in the condensate phase.

References

[1] P. B. Blakie, D. Baillie, L. Chomaz, and F. Ferlaino, Physical Review Research 2, 043318 (2020).

[2] J. Smith, D Baillie, and P. B. Blakie (in preparation).

Collective (Higgs) excitation branch in the broken pair continuum of pair-condensed spin 1/2 Fermi gases

Yvan Castin

LKB, Ecole Normale Supérieure, Paris (France)

The pair-condensed unpolarized spin $1/2$ Fermi gases exhibit a collective excitation branch in their broken pair continuum (V.A. Andrianov, V.N. Popov, 1976), sometimes called the Higgs branch. We carried out an in-depth study of it at zero temperature [1]. We start from the eigenenergy equation deduced from the linearized time-dependent BCS theory, which is equivalent to Anderson's RPA, then we carry out its analytical continuation to the lower complex half-plane through its branch cut, which is essential to find the collective mode. We compute both the complex dispersion relation and the spectral weights (quasiparticle residues) of the branch.

In the case of so-called BCS superconductors (with charged fermions) where the effect of the crystal lattice is replaced by a short range attractive interaction, but where the Coulomb interaction is taken into account, we restrict ourselves to the weak coupling limit $\Delta/\mu \to 0^+$ (Δ is the order parameter, μ the chemical potential) and to wavenumbers $q = O(1/\xi)$ where ξ is the size of a Cooper pair ; when the complex energy z_q is expressed in units of Δ and q in units of $1/\xi$, the branch follows a universal law that we determine, insensitive to the Coulomb interaction.

In the case of cold atoms in the BEC-BCS crossover, the fermions are neutral and only the contact interaction remains, but the coupling Δ/μ can take arbitrary values, and we study the branch at any wave number q. At weak coupling, we predict three scales, the one already mentioned $q \approx 1/\xi$, the one $q \approx (\Delta/\mu)^{-1/3}/\xi$ where the real part of the dispersion relation admits a minimum and that $q \approx (\mu/\Delta)/\xi \approx k_F$ (k_F is the Fermi wave number) where the branch reaches the edge of its existence domain. Near the point of zero chemical potential on the BCS side, $\mu/\Delta \to 0^+$, where $\xi \approx k_F$, we find the two scales $q \approx (\mu/\Delta)^{1/2}/\xi$ and $q \approx 1/\xi$. In any case, the branch has a limit of 2Δ and a quadratic start at $q = 0$, in accordance with what is expected of a Higgs branch, and should be observable at low q in the response of the gas to a laser Bragg excitation, if one measures the perturbation induced on the modulus of the order parameter rather than on the density [2]. On the BEC side ($\mu < 0$), we also find a Higgs branch of this type (searched in vain by T. Cea, C. Castellani, G. Seibold, L. Benfatto, 2015) but only for $\Delta/|\mu| <0.222$; it should be noted that, in this case, the starting point 2Δ of the branch is strictly below the edge of the broken pair continuum $2(\Delta^2 + \mu^2)^{1/2}$, unlike what happens on the side $\mu > 0$ (where the edge of the continuum is exactly 2Δ in BCS theory).

If time permits, we will mention, in the case of cold atoms, the existence of more exotic branches, with a hypoacoustic $z_q \approx q^{3/2}$ or hyperacoustic zero-energy start $z_q \approx q^{4/5}$.

References

[1] Y. Castin, H. Kurkjian, "Branche d'excitation collective du continuum dans les gaz de fermions condensés par paires : étude analytique et lois d'échelle", Comptes Rendus Physique **21**, 253 (2020).

[2] Y. Castin, "Spectroscopie de Bragg et mode du continuum de paire brisée dans un gaz de fermions superfluide", Comptes Rendus Physique **21**, 203 (2020).

Many-Body Chemistry
-- Reactions of Quantum Degenerate Molecules

C. Chin

James Franck Institute, Enrico Fermi institute, and Department of Physics,
University of Chicago, Chicago, IL 60637, USA
E-mail: cchin@uchicago.edu

Chemical reactions in the quantum degenerate regime are described by nonlinear mixing of matterwave fields. Quantum coherence and bosonic enhancement are two unique features of many-body reactions involving bosonic reactants and products. Such collective reactions of chemicals, dubbed "super-chemistry", is an elusive goal in quantum chemistry research. Here we report the observation of coherent and collective reactive coupling between Bose condensed atoms and molecules near a Feshbach resonance [1]. Starting from an atomic condensate, the reaction begins with a rapid formation of molecules, followed by oscillations of their populations in the equilibration process. Faster oscillations are observed in samples with higher densities, indicating bosonic enhancement [2]. We present a quantum field model which describes the dynamics and identifies three-body recombination as the dominant reaction process [2]. Our findings exemplify the highly sought-after quantum many-body chemistry and offer a new paradigm for the control of quantum chemical reactions.

References

[1] Z. Zhang, L. Chen, K. Yao and C. Chin, Nature **592**, 708 (2021)
[2] Z. Zhang, S. Nagata, K. Yao and C. Chin, ArXiv: 2207.08295

Many-body physics with quantum gases of magnetic lanthanide atoms: advances and new trends

L. Chomaz[1]

[1]*Physics Institute, Heidelberg University, Heidelberg, Germany*

Lanthanide atoms have remarkable properties that are mainly underpinned by their remarkable ground-state electronic configuration, featuring a partially filled 4f shell submerged below a filled 6s shell. This configuration gives them among the largest magnetic moments in the periodic table and also allows for efficient laser-based manipulation and cooling schemes. About a decade ago, the first quantum degenerate gases of dysprosium and erbium (followed more recently by thulium and europium) were achieved. This has opened up new avenues of research where the role of long-range anisotropic dipole-dipole interactions can be studied in a pristine and well-controllable quantum setting and in a weak interaction regime [1]. In the recent years, this has led to the discovery of novel many-body quantum states in three-dimensional lanthanide Bose gases, including roton-like excitations, as well as liquid-like droplet, droplet-crystal, and supersolid-like steady states. In this talk, I will highlight key results obtained in my former working group and report on the development of my research at the University of Heidelberg working on such systems.

References

[1] L. Chomaz, I. Ferrier-Barbut, F. Ferlaino, B. Laburthe-Tolra, B. L. Lev, & T. Pfau, Dipolar physics: A review of experiments with magnetic quantum gases. *arXiv preprint* ***arXiv:2201.02672*** *(2022).*

Full counting statistics of interacting lattice gases after an expansion: role of the condensate depletion on the many-body coherence

J.-P. Bureik, G. Hercé, A. Tenart, A. Dareau, A. Aspect, D. Clément

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

We study the full counting statistics (FCS) of quantum gases in samples of thousands of interacting bosons, detected atom-by-atom after a long free-fall expansion. In this far-field configuration, the FCS reveals the many-body coherence from which we characterize iconic states of interacting lattice bosons by deducing the normalized correlations $g^{(n)}(0)$ up to the order n=6. In Mott insulators, we find a thermal FCS characterized by perfectly-contrasted correlations $g^{(n)}(0)=n!$. In interacting Bose superfluids, we observe small deviations to the Poisson FCS and to the ideal values $g^{(n)}(0)=1$ expected for a pure condensate. To describe these deviations, we introduce a heuristic model that includes an incoherent contribution attributed to the depletion of the condensate. The predictions of the model agree quantitatively with our measurements over a large range of interaction strengths that includes the regime where the condensate is strongly depleted by interactions. These results suggest that the condensate component exhibits a full coherence $g^{(n)}(0)=1$ at any order n up to n=6 and at arbitrary interaction strengths. The approach demonstrated here is readily extendable to characterize a large variety of interacting quantum states and phase transitions.

References

[1] G. Hercé, J.-P. Bureik, A. Tenart, A. Dareau, A. Aspect, D. Clément, arXiv:2207.14070 (2022).

Polaron interaction in superfluids

Tilman Enss[1]

[1]*Institute for Theoretical Physics, Heidelberg University, Germany*

We investigate the induced Casimir interaction between two impurities in superfluid atomic gases. With the help of effective field theory (EFT) for a Galilean invariant superfluid, we show that the induced impurity-impurity potential at long distances does not fall off exponentially but instead exhibits a universal power-law scaling. We find that the exchange of two phonons leads to a relativistic van der Waals-like attraction (~1/r^7) at zero temperature and a nonrelativistic van der Waals attraction (~T/r^6) at finite temperature. Our EFT formulation applies not only to weakly coupled Bose or Fermi superfluids but also to strongly correlated unitary fermions with weakly coupled impurities. The sound velocity controls the magnitude of the van der Waals potential, which we evaluate for the fermionic superfluid in the BCS-BEC crossover. This presentation is based on joint work with Keisuke Fujii and Masaru Hongo.

References

[1] K. Fujii, M. Hongo, T. Enss, *Universal van der Waals force between heavy polarons in superfluids,* arXiv:2206.01048.

Anomalous loss of coherence of strongly interacting bosons in optical lattices

R. Bouganne[1], M. Bosch Aguilera[1], R. Vatré, A. Ghermaoui[1], J. Beugnon[1] and F. Gerbier[1]

[1] *Laboratoire Kastler Brossel, Collège de France, ENS-PSL Research University, Sorbonne Université, CNRS, 11 place Marcelin-Berthelot, 75005 Paris*

An isolated atom in a well-defined momentum state provides a textbook example of a dissipative quantum system when exposed to a near-resonant laser. The laser drives absorption-stimulated emission cycles and creates well-defined quantum superpositions of atomic internal and external states. The laser-driven Rabi oscillation is however in competition with spontaneous emission processes, arising from the coupling of the atom to the electromagnetic vacuum. Spontaneous emission introduces introduces random momentum changes, leading to a diffusive dynamics of the initially well-defined momentum. The width of the continuously broadening momentum distribution scales as the square root of time, typical of Brownian motion. This momentum diffusion process is well-known in quantum optics and limits the temperature achievable in laser cooling.

In this talk, I will discuss a series of experiments where we studied the spatial coherence of ultracold bosonic gases in optical lattices exposed to a near-resonant light [1]. We observe that momentum diffusion/decay of spatial coherences is anomalously slow when the atoms are strongly interacting, with a sub-diffusive dynamics and a momentum width scaling as $t^{1/4}$. Our observations support the theory of Poletti *et al.* [2], where the dynamics at long-times is explained by the formation of "long-lived" clusters of atoms with higher occupancy than the average. Such clusters decay slowly (through high-order processes) due to their energy mismatch with more typical configurations, leading to a sub-diffusive dynamics in Fock space that is at the root of the momentum subdiffusion observed in the experiment.

References

[1] R. Bouganne, M. Bosch Aguilera, A. Ghermaoui, J. Beugnon, and F. Gerbier. Nat. Phys. **16**, 21 (2020).

[2] D. Poletti, J.-S. Bernier, A. Georges, and C. Kollath. Phys. Rev. Lett. **109**, 045302 (2012); D. Poletti, P. Barmettler, A. Georges, and C. Kollath, Phys. Rev. Lett. **111**, 195301 (2013).

Waveguide QED with Rydberg superatoms

Hannes Busche[1], Nina Stiesdal[1], Jan Kumlin[2], Kevin Kleinbeck[2], Lukas Ahlheit[1], Cedric Wind[1], Julia Gamper[1], Hans Peter Büchler[2], and Sebastian Hofferberth[1]

[1]*Institut für angewandte Physik, University of Bonn, Germany*

[2]*Institute for Theoretical Physics III and Center for Integrated Quantum Science and Technology, University of Stuttgart, Germany*

Rydberg quantum optics allows to create strong optical nonlinearites at the level of individual photons by mapping the strong interactions between Rydberg excitations onto optical photons. The interactions lead to a blockade effect such that an optical medium smaller than the blockaded volume only supports a single excitation which is collectively shared amongst all blockaded atoms forming a 'Rydberg superatom'. Thanks to the collective nature of the excitation, the superatom effectively represents a single emitter with a strongly enhanced coupling to few-photon probe fields with directional emission into the initial probe mode [1].

This makes Rydberg superatoms an ideal platform to study the interaction of individual two-level emitters with quantised light fields. The interaction leads for example to the emergence of two- and three-photon correlations in the transmitted light, while exchange interactions between the constituent atoms within a superatom lead to non-trivial decay dynamics of the collective state [2].

When combined with controlled dephasing into dark, collectively excited states, we exploit the strong photon-emitter coupling to subtract exact photon numbers from incoming light fields providing a means to precisely manipulate their quantum state [3]. To this end, we cascade multiple superatoms in 1D chain along mode of the probe field. In the regime of low dephasing, such a cascaded quantum system of multiple superatoms also offers the prospect to observe photon-mediated interactions and entanglement along the probe mode which effectively forms a freespace `waveguide'.

References

[1] A. Paris-Mandoki, C. Braun, J. Kumlin, C. Tresp, I. Mirgorodskiy, F. Christaller, H. P. Büchler, and S. Hofferberth, Phys. Rev. X 7, 041010 (2017).

[2] N. Stiesdal, H. Busche, J. Kumlin, K. Kleinbeck, H. P. Büchler and S. Hofferberth, Phys. Rev. Research 2, 043339 (2020).

[3] N. Stiesdal, H. Busche, K. Kleinbeck, J. Kumlin, M. G. Hansen, H. P. Büchler and S. Hofferberth, Nat. Commun. 12, 4328 (2021).

Correlated Topological Quantum States in Ultracold Atoms

W. Hofstetter

Goethe-University Frankfurt, Institute for Theoretical Physics, Germany

Ultracold atoms in optical lattices are powerful quantum simulators for strongly correlated systems. With synthetic gauge fields, induced by time-periodic driving, they can simulate interacting topological states of matter. I will address open challenges:

Quantum gases are mesoscopic and have soft boundaries. We propose an interacting topological interface that allows to experimentally observe edge modes via quantum gas microscopy. We also show that the topology of an interacting Chern insulator is approximately encoded in the single-particle density matrix, which can be measured in time-of-flight experiments.

Disorder usually impedes coherent transport. Together with gauge fields it can remarkably induce a topological phase with quantized transport. We show that strong correlations can even enhance this effect.

Quantum Physics in Connected Worlds

Joseph Tindall[1], Amy Searle[1], Abdulla Alhajri[1,2], Dieter Jaksch[3,4,1]

[1]Department of Physics, University of Oxford
[2]Technology Innovation Institute, Abu Dhabi, UAE
[3]The Hamburg Centre for Ultrafast Imaging, Hamburg, Germany
[4]Institut für Laserphysik, Universität Hamburg, Hamburg, Germany

Theoretical research into many-body quantum systems has focused almost exclusively on regular structures which have a small, simple unit cell and where only a vanishingly small number of pairs of the constituents directly interact. Motivated by rapid advances in control over the pairwise interactions and geometries in ultracold atomic systems [1] and other quantum simulators, we determine the fate of many-body spin systems on more general, arbitrary graphs [2].
When placing the minimum possible constraints on the underlying graph, we prove and observe how, with certainty in the thermodynamic limit, such systems behave like a single collective spin and exhibit no many-body physics. We thus understand the emergence of complex many-body physics as dependent on ‘exceptional’, geometrically constrained structures such as the low-dimensional, regular ones found in nature. Within the space of highly connected graphs, we identify hitherto unknown exceptions via their inhomogeneity and use state-of-the-art Matrix Product State algorithms to observe how complexity is heralded in these systems by a large degree of entanglement and highly non-uniform correlation functions. By bringing a graph-theoretic approach to the realm of many-body physics, our work paves the way for the discovery and exploitation of a whole class of geometries which can host uniquely complex phases of matter and might be realized by near-future ultracold atom quantum simulators [3].

References

[1] See e.g. A. Browaeys and T. Lahaye, Nature Physics **16,** 132 (2020).
[2] J. Tindall, A. Searle, A. Alhajri, and D. Jaksch, arXiv:2205.07924.
[3] Quantum computers could create completely new forms of matter | New Scientist

Effects of quantum mechanical identity in scattering of atoms and light

Niels Kjærgaard

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

Departing from Rutherford and Chadwick's 100-year-old experiments on "The scattering of α-particles by Helium" [1,2], I will discuss cold atomic collisions between pairs of indistinguishable bosons [3,4] and fermions [5] observed using a laser-based collider for ultracold atoms. In the realm of quantum mechanics, identity profoundly influences the collisions between particles. For example, colliding indistinguishable fermions cannot scatter sideways as a result of Pauli exclusion [5]. Pauli exclusion also affects the scattering of probe light from a quantum degenerate Fermi gas. In particular, degeneracy leads to a suppression of fluorescence [6-8] and I will present our experimental observation of Pauli blocking of light scattering for fermions [6], contrasting it to the bosonic case.

References

[1] E. Rutherford & J. Chadwick, Phil. Mag. **4**, 605 (1927)
[2] N. Kjærgaard, J. R. Soc. N. Z. **51**, 489 (2021)
[3] M. Chilcott, R Thomas & N. Kjærgaard, Phys. Rev. Res. **3**, 033209 (2021)
[4] M. Chilcott, J.F.R. Croft, R. Thomas & N. Kjærgaard, Phys. Rev. A **106**, 023303 (2022)
[5] R. Thomas, et al., Nat. Commun. **7**, 12069 (2016)
[6] A.B. Deb & N. Kjærgaard, Science **374**, 972 (2021)
[7] Y. Margalit, Y.-K. Lu, F.Ç. Top, W. Ketterle, Science **374**, 976 (2021)
[8] C. Sanner et al., Science **374**, 979 (2021)

Characterizing sine Gordon dynamics with quantum gas microscopes

M. Knap[1]

[1]*Department of Physics, Technical University of Munich, Germany*

The sine-Gordon field theory emerges as the low-energy description in a wealth of quantum many-body systems. As a particular realization we study tunnel coupled Bose Hubbard chains and observe the emergent sine-Gordon dynamics deep in the quantum regime. We use matrix-product state techniques to numerically characterize the low-energy sector of the system and compare it with the exact field theory predictions. From this comparison, we obtain quantitative boundaries for the validity of the sine-Gordon description. We provide encompassing evidence for the emergent field theory by probing its rich spectrum and by observing the signatures of integrable dynamics in scattering events [1]. We also discuss the preparation and detection of the fundamental topological excitations of the sine-Gordon field theory, the solitons, using quantum gas microscopes [2].

References

[1] E. Wybo, M. Knap, A. Bastianello, PRB **106**, 075102 (2022)

[2] E. Wybo, et al. in preparation.

Supersolidity in dipolar Bose-Einstein condensates

T. Langen

5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, University of Stuttgart, Pfaffenwaldring 57, 70180 Stuttgart, Germany

I will discuss a series of experimental and theoretical studies of supersolidity in dipolar Bose-Einstein condensates. In the first part of the talk, I will focus on quantum gases of magnetic dysprosium atoms. I will present observations of droplet supersolids in cigar-shaped geometries, the characterization of fluctuations and elementary excitations across the BEC-to-supersolid phase transition, as well as extensive theoretical studies of the respective excitation spectra. Notably, the latter include characteristic Goldstone and Higgs modes, which proof the superfluid nature of the supersolid states in the experiments. Moreover, in oblate geometries we experimentally study angular and radial roton modes and their role in the crystallization of the system. In particular, we theoretically identify regimes where spontaneous rotational symmetry breaking leads to the emergence of a 2D droplet supersolid. We further predict the existence of a large variety of novel phases that go beyond the paradigm of droplet supersolidity, and which have strong connections to the field of pattern formation. These phases include honeycomb and labyrinthine states, as well as a pumpkin phase. In the second part of the talk, I will discuss how such exotic supersolid states could be explored further in future experiments with Bose-Einstein condensates of strongly dipolar molecules.

References

[1] F. Böttcher *et al.*, Phys. Rev. X **9**, 011051 (2019)
[2] M. Guo *et al.*, Nature **574**, 386–389 (2019)
[3] J. Hertkorn *et al.*, Phys. Rev. X **11**, 011037 (2021)
[4] J.-N. Schmidt *et al.*, Phys. Rev. Lett. 126, 193002 (2021)
[5] J. Hertkorn *et al.*, Phys. Rev. Research **3**, 033125 (2021)
[6] J. Hertkorn *et al.*, Phys. Rev. Lett. **127**, 155301 (2021)
[7] M. Schmidt *et al.*, Phys. Rev. Research **4**, 013235 (2022)

Studying ultracold bubbles in orbital microgravity with the NASA Cold Atom Laboratory

N. Lundblad[1]

[1]*Bates College, Department of Physics and Astronomy, Lewiston, USA*

Exploring the effects of geometry, topology, dimensionality, and interactions on ultracold atomic ensembles has proven to be a continually fruitful line of inquiry. One heretofore unexplored configuration for such ensembles is that of a bubble or shell, where trapped atoms are confined in the vicinity of a spherical or ellipsoidal surface. Such a system could offer new collective modes, topologically-sensitive behavior of quantized vortices, self-interference and shell collapse, as well as the exploration of trapped ultracold systems with mm-scale spatial extent. While techniques for the generation of bubble-shaped traps have been known since 2001[1], terrestrial gravity has thus far prevented the observation of ultracold bubbles. With the construction of the NASA Cold Atom Lab (CAL) facility and its subsequent delivery in 2018 to the International Space Station (ISS) and commissioning as an orbital Bose-Einstein condensate (BEC) user facility, experimental atomic physics schemes that require a sustained microgravity environment are now possible. I will present recent CAL observations of trapped bubbles of ultracold atoms, including a variety of bubble-trap configurations that are possible with this apparatus[2]. I will also discuss the thermodynamics of ultracold bubbles and review open questions being explored in the ongoing second science run of CAL aboard ISS, which feature improved bubble aspect ratios and filling as well as improved imaging; I will also review upcoming changes to the CAL facility aimed at improved BEC quality, as well as recent progress made with shell structures in terrestrial laboratories.

References

[1] O. Zobay and B. M. Garraway, Phys. Rev. Lett. **86**, 1195 (2001)
[2] Carollo et al., Nature **606**, 281-286 (2022)

Supersolidity, Bloch oscillations and vortices in dipolar quantum gases

Manfred J. Mark[1, 2, *]

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

Since strongly dipolar quantum gases made from lanthanide atoms were successfully brought to degeneracy 10 years ago, they have proven to be a rich source of new and fascinating phenomena arising from the long-range and anisotropic dipole-dipole interactions. Here, we will present the latest results from our erbium and dysprosium quantum gas experiments in Innsbruck. Following the recent discovery of supersolid states in dipolar gases, we have studied the lifecycle of these intriguing states of matter from its formations to death [1]. Afterwards our efforts have been directed toward creating and studying states with a greater spatial extent that has eventually led us to the observation of supersolidity in two dimensions [2]. Next, we investigated the properties of strongly dipolar gases within an array of two-dimensional traps [3]. Here, we used Bloch oscillations to study the importance of beyond mean-field quantum fluctuations on the properties of the system and detected a transition to a stable self-focusing state which occupies only a single lattice plane. Our calculated phase diagram confirms this observation and predicts the possibility of preparing dipolar solitons in such systems. Finally, we show our most recent results on inducing vortices in dipolar systems [4]. Using magnetostirring - a novel technique only possible due to dipole-dipole interactions - we were able to create vortices in a dipolar BEC. Moreover, we observed the alignment of the vortex cores along stripes parallel to the orientation of the magnetic field, which is absent when turning the magnetic field perpendicular to the plane of rotation.

[1] M. Sohmen et al., Phys. Rev. Lett. **126**, 233401 (2021)
[2] M. A. Norcia et al., Nature **596**, 357-361 (2021)
[3] G. Natale et al., arXiv:2205.03280 (accepted for publication in Communications Physics) (2022)
[4] L. Klaus et al., arXiv:2206.12265 (2022)

* manfred.mark@uibk.ac.at

Non-Equilibrium Dynamics and Nanofriction in Ion Coulomb Crystals

Lars Timm[1], Jan Kiethe[2], Hendrik Weimer[1], Luis Santos[1], and Tanja E. Mehlstäubler[1,2]

[1]Leibniz Universität Hannover, 30167 Hannover, Germany

[2]PTB, 38116 Braunschweig, Germany

Single trapped and laser-cooled ions in Paul traps allow for a high degree of control of atomic quantum systems. They are the basis for modern atomic clocks, quantum computers and quantum simulators. We aim to use ion Coulomb crystals, i.e. many-body systems with complex dynamics, for precision spectroscopy. This paves the way to novel optical frequency standards for applications such as relativistic geodesy and quantum simulators in which complex dynamics becomes accessible with atomic resolution. The high-level of control of self-organized Coulomb crystals opens up a fascinating insight into the non-equilibrium dynamics of coupled many-body systems, displaying atomic friction and symmetry-breaking phase transitions. We discuss the creation of topological defects in 2D crystals and present recent results on the study of tribology and transport mediated by the topological defect, discussing both classical and quantum regimes.

References

[1] K. Pyka *et al.,* Nat. Commun. **4,** 2291 (2013)
[2] J. Kiethe *et al.,* Nat. Commun. **8,** 15364 (2017)
[3] J. Kiethe *et al.,* New J. Phys. **20,** 123017 (2018)
[4] L. Timm, *et al*., Phys. Rev. Research **2**, 033198 (2020)
[5] L. Timm, *et al*., Phys. Rev. Research **3**, 043141 (2021)

Kardar-Parisi-Zhang universality in a one-dimensional polariton condensate

Q. Fontaine,1 D. Squizzato,2, 3, 4 F. Baboux,5, 6 I. Amelio,7 A. Lemaıtre,1 M. Morassi,1 I. Sagnes,1 L. Le Gratiet,1 A. Harouri,1 M. Wouters,8 I. Carusotto,7 A. Amo,9 M. Richard,10 A. Minguzzi,2 L. Canet,2 S. Ravets,1 and J. Bloch 1

1 Universit´e Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies (C2N), 91120, Palaiseau, France
2 Univ. Grenoble Alpes and CNRS, Laboratoire de Physique et Mod´elisation des Milieux Condenses, 38000 Grenoble, France.
3 Dipartimento di Fisica, Universit`a La Sapienza - 00185 Rome, Italy.
4 Istituto Sistemi Complessi, Consiglio Nazionale delle Ricerche, Universit`a La Sapienza - 00185 Rome, Italy.
5 Universit´e Paris-Saclay, CNRS, Centre de Nanosciences et de Nanotechnologies (C2N), 91120, Palaiseau, France.
6 Laboratoire Mat´eriaux et Ph´enom`enes Quantiques, Universit´e de Paris, CNRS-UMR 7162, Paris 75013, France.
7 INO-CNR BEC Center and Dipartimento di Fisica, Universit`a di Trento, 38123 Povo, Italy.
8TQC, Universiteit Antwerpen, Universiteitsplein 1, B-2610 Antwerpen, Belgium.
9 Univ. Lille, CNRS, UMR 8523 – PhLAM – Physique des Lasers Atomes et Mol´ecules, F-59000 Lille, France
10 Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Neel, 38000 Grenoble, France.

Revealing universal behaviors is a hallmark of statistical physics. Phenomena such as the stochastic growth of crystalline surfaces, of interfaces in bacterial colonies and spin transport in quantum magnets all belong to the same universality class, despite the great plurality of physical mechanisms they involve at the microscopic level. This universality stems from a common underlying effective dynamics governed by the non-linear stochastic Kardar-Parisi-Zhang (KPZ) equation. Recent theoretical works suggest that this dynamics also emerges in the phase of excitons polaritons, out-of-equilibrium systems displaying macroscopic spontaneous coherence. I will report on our common theory-experimental work demonstrating that the evolution of the phase in a driven-dissipative one-dimensional polariton condensate falls in the KPZ universality class. Our result relies on the measurement of KPZ space-time scaling laws, combined with a theoretical analysis that reveals other key signatures of this universality class as the probability distribution. Our study highlights fundamental physical differences between out-of-equilibrium condensates and their equilibrium counterparts, and open a paradigm for exploring universal behaviors in driven open systems.

References

[1] Q. Fontaine et al, Nature **608**, 687–691 (2022)

Fermions in an Optical Box

N. Navon[1,2]

[1] Department of Physics, Yale University, New Haven, Connecticut 06520, USA
[2] Yale Quantum Institute, Yale University, New Haven, Connecticut 06520, USA

For the past two decades harmonically trapped ultracold atomic gases have been used with great success to study fundamental many-body physics in flexible experimental settings. However, the resulting gas density inhomogeneity in those traps makes it challenging to study paradigmatic uniform-system physics (such as critical behavior near phase transitions) or complex quantum dynamics.
The realization of homogeneous quantum gases trapped in optical boxes has marked a milestone in the quantum simulation program with ultracold atoms [1]. These textbook systems have proved to be a powerful playground by simplifying the interpretation of experimental measurements, by making more direct connections to theories of the many-body problem that generally rely on the translational symmetry of the system, and by altogether enabling previously inaccessible experiments.

I will present a set of studies with ultracold fermions trapped in a box of light. This system is particularly suitable to study problems of fermion stability, of which I will discuss two cases: the spin-1/2 Fermi gas with repulsive contact interactions [2], and the three-component Fermi gas with spin-population imbalance. Both studies lead to surprising results, highlighting how spatial homogeneity not only simplifies the connection between experiments and theory, but can also unveil unexpected outcomes. Finally, I will discuss two ongoing efforts to tackle far-from-equilibrium dynamics of uniform fermions. One focuses on an impurity embedded in a Fermi bath and strongly driven between internal states; the second one aims at understanding the strongly interacting fermion gas spatially driven on a large length scale, for which we observe nonlinear response of the lowest-lying collective mode.

References

[1] N. Navon, R.P. Smith, Z. Hadzibabic, Nat. Phys. 17, 1334 (2021)
[2] Y. Ji et al., arXiv:2204.03644, Phys. Lev. Lett (in press, 2022)

Ultracold Bose Gases in Driven-Dissipative Environments

H. Ott[1]

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

Driven-dissipative systems are characterized by the appearance of steady-states. Upon parameter change, they can undergo dissipative phase transitions between different types of steady-states One of the paradigmatic examples for a first order dissipative phase transition is the driven nonlinear single-mode optical resonator. I will report on the corresponding realization within an ultracold bosonic gas, which generalizes the single-mode system to many modes and stronger interactions [1]. We measure the effective Liouvillian gap of the system and find evidence for a first order dissipative phase transition. Due to the multi-mode nature of the system, the microscopic dynamics is much richer and allows us to identify a non-equilibrium condensation process. I will also present results on a periodically driven external potential, which constitutes the cold atom analogue of a Kapitza pendulum. The characteristics, the stability and the future perspectives of this system are discussed.

References

[1] J. Benary et al., arXiv:2203.09896 (2022)
[2] J. Jiang et al., arXiv:2112.10954 (2022)

Ferromagnetism in (sodium) spinor Bose-Einstein condensates

A. Recati

INO-CNR BEC Center and Dipartimento di Fisica, Trento University, I-38123 Povo Italy

In the present talk we review the properties of a spin-1/2 Bose-Einstein condensate (BEC) in presence of both longitudinal and transverse external fields.
The system has very peculiar properties not only with respect to the single component BEC, but also to BEC mixtures (where the atom number of each species is conserved).
In particular the system can exhibit a para- to ferro-magnetic transition, has a gapped spin spectrum, and can sustain peculiar magnetic defects.
Interestingly, most of the peculiar properties are due to the system being an analog of a (non-dissipative) ferromagnetic material well described by the so-called Landau-Lifhsitz equation.
We then present some of the system's properties that have very recently been tested experimentally in our lab using Na-23 atomic gases. In particular we measured the excitation spectrum by modulating the trapping potential and generating Faraday patterns [1], we started characterizing the ferromagnetic transition [2] as well as the fate of highly out-of-equilibrium initial states [3].

References

[1] R. Cuminotti et al., Phys. Rev. Lett. **128**, 210401 (2022)
[2] R. Cuminotti et al.,, arXiv:2209.13235
[3] A. Farolfi et al., Nat. Phys. **17**, 1359 (2021)

Quantum Simulation with spin-orbit-coupled fermions in optical lattices

Ana Maria Rey

University of Colorado, JILA, Boulder, USA

Understanding the behavior of strongly interacting electrons in solids under strong magnetic fields has been a paradigmatic goal of physics research. Ultracold alkaline-earth atoms (AEAs) loaded in optical lattices featuring a clean, isolated and controllable environment are emerging as powerful quantum simulators which can shed light into this challenging problem. A unique appeal of AEAs fermionic atoms featuring n internal levels is their unique Su(n) symmetric collisions. Here I will discuss our studies on dynamical behaviors of SU(n) interacting fermionic AEAs subject to an effective magnetic field. This system can be engineered by coupling the n internal levels of the atoms, which can be visualized as a synthetic spatial dimension, by appropriate laser drives. I will focus on the dense and strongly interacting regime where our studies reveal rich and interesting behaviors generated by the interplay between strong SU(n) interactions, the external magnetic flux and particle motion all observable at conditions currently accessible in state-of-the art experiments.

Dicke Transition in Open Many-Body Systems Determined by Fluctuation Effects

Achim Rosch

Institute for Theoretical Physics, University of Cologne, Germany

We show [1] that fluctuation effects are essential to determine the steady state of ultracold quantum systems in cavities. We study the Dicke transition of interacting many-particle systems strongly coupled to the light of a lossy cavity. A mean-field approach is combined with a perturbative treatment of fluctuations beyond mean field, which becomes exact in the thermodynamic limit. These fluctuations completely change the nature of the steady state, determine the thermal character of the transition, and lead to universal properties of the emerging self-organized states. We validate our results by comparing them with time-dependent matrix-product-state calculations by the Kollath group.

References

[1] Alla V. Bezvershenko, Catalin-Mihai Halati, Ameneh Sheikhan, Corinna Kollath, Achim Rosch, Phys. Rev. Lett. **127**, 173606 (2021).

The Fock States Sampling method

Kazimierz Rzążewski

Center for Theoretical Physics, Polish Academy of Sciences
Al. Lotników 32/46, 02-668 Warsaw, Poland

Thermal fluctuations of Bose-Einstein condensate are of interest ever since E. Schrödinger noticed their dependence on the choice of a statistical ensemble. Widely used the grand statistical ensemble, when applied to an isolated system yielding unphysical results. The problem of fluctuations was a hot topic after the first experiments on BEC. Asymptotic results were obtained and recurrence relations were derived for partition functions in microcanonical and canonical ensembles. The role of weak collisions remains controversial. Recently, the fluctuations were finally measured by the group of Jan Arlt from Aarhus [1, 2]. We are providing theoretical background. In particular, in [2] we argue that the experiment unveiled for the first time microcanonical fluctuations of the condensate. We developed a novel method of computing the statistics of the non-zero temperature properties of the Bose gas, named the Fock States Sampling method, that gives access to both, canonical and microcanonical statistics for up to 100 000 particles.
The method is also applicable to the weakly interacting gas trapped in a box. In this case, results for the interaction-induced shifts of the critical temperature will be revisited. [3].

References

[1]. Kristensen, MA , Christensen, MB; Gajdacz, M ; Iglicki, M, Pawlowski, K ; Klempt, C ; Sherson, JF, Rzążewski, K. ; Hilliard, AJ Arlt, JJ, Observation of Atom Number Fluctuations in a Bose-Einstein Condensate, Phys. Rev. Lett.122, 163601 (2019)

[2]. M. B. Christensen, T. Vibel, A. J. Hilliard, M. B. Kruk, K. Pawłowski, D. Hryniuk, K. Rzążewski, M. A. Kristensen, and J. J. Arlt, Observation of Microcanonical Atom Number Fluctuations in a Bose-Einstein Condensate, Phys. Rev. Lett.126, 153601, (2021),

[3]. Maciej Bartłomiej Kruk, Dawid Hryniuk, Mick Kristensen, Toke Vibel, Krzysztof Pawłowski, Jan Arlt, Kazimierz Rzążewski, Microcanonical and Canonical Fluctuations in Bose-Einstein Condensates -- Fock state sampling approach, arXiv:2207.04536

From a polaron into a cluster: the fate of an impurity in a Bose Einstein condensate

Richard Schmidt[1]

[1]*Institute for Theoretical Physics, Universität Heidelberg, Germany*

In ultracold atomic gases, a unique interplay arises between phenomena known from condensed matter, few-body physics and chemistry. Similar to an electron in a solid, a quantum impurity in an atomic Bose-Einstein condensate is dressed by excitations from the medium, forming a polaron quasiparticle with modified properties. At the same time, the atomic impurity can undergo the chemical reaction of three-body recombination with atoms from the BEC, which can be resonantly enhanced due to universal three-body Efimov bound states crossing the continuum. As an intriguing example of chemistry in a quantum medium, we show that such Efimov resonances are shifted to smaller interaction strengths due to participation of the polaron cloud in the bound state formation. Simultaneously, the shifted Efimov resonance marks the onset of a polaronic instability towards the decay into larger Efimov clusters and fast recombination, offering a remarkable example of how chemistry can be modified in a quantum medium.

References

[1] A. Christianen, J.I. Cirac, R. Schmidt, ”Chemistry of a light impurity in a Bose-Einstein condensate”, Phys. Rev. Lett. **128**, 183401 (2022).
[2] A. Christianen, J.I. Cirac, R. Schmidt, ”From Efimov Physics to the Bose Polaron using Gaussian States”, Phys. Rev. A **105**, 013324 (2022).

Topology in time-evolving quantum systems

M. Lu, G. H. Reid, A. R. Fritsch, A. M. Piñeiro, and I. B. Spielman

[1]*Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, Maryland, 20899, USA*

Topological invariants robustly classify gapped quantum systems in equilibrium, and phenomena such as the quantized Hall effect---the progenitor of the von Klitzing constant---are macroscopic reflections of these invariants.

In addition to dimensionality, the presence or absence of symmetries determines the possible topological invariants. Thus, these invariants remain constant provided that no gaps close and no symmetries are added or removed. For this reason, one might expect the topology of a dynamical quantum system to be similarly robust; this expectation is untrue. Instead as a system undergoes far from equilibrium evolution symmetries come and go, allowing the topology to change as well. We experimentally study these dynamics with ultracold atoms in a 1D bipartite lattice in terms of the Zak phase and a chiral winding number.

References

[1] *Dynamically Induced Symmetry Breaking and Out-of-Equilibrium Topology in a 1D Quantum System*; G. H. Reid, et al; Phys. Rev. Lett. **129** 123202 (2022).

[2] *Floquet Engineering Topological Dirac Bands*; M. Lu, et al; PRL **129** 040402 (2022).

Novel Non-equilibrium Phenomena in Quantum Fluids of Light

M. H. Szymanska[1]

[1]*Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK*

Driven-dissipative quantum fluids of light, experimentally realised in for example semiconductor microcavities, circuit or cavity QED systems, provide a unique testbed to explore new non-equilibrium quantum phenomena. I will review recent progress in this field. In particular, we show that polariton quantum fluid can exhibit a non-equilibrium order, where superfluidity is accompanied by stretched exponential decay of correlations [1]. This celebrated Kardar-Parisi-Zhang (KPZ) phase has not been achieved before in any system in 2D, and even 1D realisations have not been conclusive. I will then discuss how these systems can undergo other unconventional phase transitions and orders [2,3], and display flow properties connected but distinct from conventional superfluidity. Finally, when placed in strained honeycomb lattice potentials, polariton fluids can condense into a rotating state, the lowest Landau level, forming a vortex array and spontaneously breaking time reversal symmetry [4].

[1] A. Zamora et al, PRX 7, 041006 (2017); PRL 125, 265701 (2020); A. Ferrier et al, PRB 105, 205301 (2022)
[2] G. Dagvadorj et al, arXiv:2208.04167 (2022)
[3] G. Dagvadorj et al, PRB 104, 165301 (2021)
[4] C. Lledo et al, SciPost 12, 068 (2022)

Engineering a topological gauge theory in an optically coupled Bose-Einstein condensate

A. Frölian[1], C. S. Chisholm[1], E. Neri[1], C. R. Cabrera[1], R. Ramos[1], A. Celi[2], L. Tarruell[1,3]

[1]ICFO - Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain
[2]Departament de Física, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain
[3]ICREA, Pg. Lluís Companys 23, 08010 Barcelona, Spain

Topological gauge theories describe the low-energy properties of certain strongly correlated quantum systems through effective weakly interacting models. A prime example is the Chern-Simons theory of fractional quantum Hall states, where anyonic excitations emerge from the coupling between weakly interacting matter particles and a density-dependent gauge field. While in traditional solid-state platforms such gauge theories are only convenient theoretical constructions, engineered quantum systems enable their direct implementation and provide a fertile playground to investigate their phenomenology without the need for strong interactions. In my talk, I will report on our recent realization of a one-dimensional reduction of the Chern-Simons theory (the chiral BF theory) in a Bose-Einstein condensate. Using the local conservation laws of the theory we eliminate the gauge degrees of freedom in favor of chiral matter interactions [1], which we engineer by synthesizing optically dressed atomic states with momentum-dependent scattering properties [2]. This allows us to reveal the key properties of the chiral BF theory: the formation of chiral solitons and the emergence of an electric field generated by the system itself [2]. Our results expand the scope of quantum simulation to topological gauge theories and pave the way towards implementing analogous gauge theories in higher dimensions.

References

[1] C. S. Chisholm, A. Frölian, E. Neri, R. Ramos, L. Tarruell, and A. Celi, Encoding a one-dimensional topological gauge theory in a Raman-coupled Bose-Einstein condensate, arXiv:2204.05386.

[2] A. Frölian, C. S. Chisholm, E. Neri, C. R. Cabrera, R. Ramos, A. Celi, and L. Tarruell, Realizing a 1D topological gauge theory in an optically dressed BEC, Nature **608**, 293–297 (2022).

Higgs mode in Strongly Interacting Fermi Gases

P. Dyke[1], A. Pennings[1], I. Herrera[1], S. Hoinka[1], S. Musolino[2], D. Ahmed-Braun[2], S. Kokkelmans[2], H. Kurkjian[3], V. Colussi[4], C. J. Vale[1]

[1]Swinburne University of Technology, Hawthorn VIC 3122, Australia,
[2]Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands,
[3]Université de Toulouse, CNRS, UPS, 31400, Toulouse, France,
[4]Università di Trento 38123 Povo, Trento, Italy.

Interaction quenches in atomic Fermi superfluids can excite oscillations of the order parameter, commonly known as the Higgs amplitude mode. Here we use Bragg spectroscopy to locally measure the response of a Fermi gas following a rapid quench, which directly reveals these amplitude oscillations. Within the superfluid phase, the strength of the Higgs excitation displays a strong temperature dependence, in good agreement with time-dependent BCS theory. The oscillation frequency provides a lower bound on the energy required to break superfluid pairs and is found to be relatively constant as a function of temperature at unitarity. Away from unitarity the Higgs frequency changes significantly with interaction strength, showing the evolution of the pairing gap. Higgs oscillations exhibit a power-law decay with a damping exponent that changes smoothly from the BCS to molecular Bose-Einstein condensate regimes.

Superfluid transport through a dissipative quantum point contact

M.-Z. Huang[1], J. Mohan[1], A.-M. Visuri[2], P. Fabritius[1], M. Talebi[1], S. Wili[1], S. Uchino[3], T. Giamarchi[4], T. Esslinger[1]

[1]*Department of Physics, ETH Zürich, 8093 Zürich, Switzerland*
[2]*Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany*
[3]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
[4]*Department of Quantum Matter Physics, University of Geneva,*
24 quai Ernest-Ansermet, 1211 Geneva, Switzerland

We study theoretically and experimentally the superfluid transport of ultracold fermionic atoms through a quantum point contact with a local particle loss. In the absence of losses, superconducting contacts are known to exhibit multiple Andreev reflections - a high-order cotunneling of a quasiparticle together with multiple Cooper pairs - which gives rise to a current at chemical potential biases below the energy gap. We develop a model the lossy quantum point contact where the superfluid reservoirs are connected via tunneling to a dissipative site and interactions are taken into account in a mean-field approximation. We compute nonequilibrium observables using the Keldysh formalism and find that the current generated by the seemingly delicate high-order tunneling process is surprisingly robust to particle losses. This result agrees with experimental data: we apply a pair-breaking, spin-dependent dissipation at the contact and observe that the characteristic non-Ohmic superfluid transport survives even at dissipation strength larger than the superfluid gap [1].

References

[1] M.-Z. Huang et al., Superfluid current through a dissipative quantum point contact, arXiv:2210.03371

Using vortices as probes of quantum many-body systems

K. E. Wilson[1]

[1]*University of Strathclyde, Glasgow, United Kingdom*

In complex, macroscopic systems, unexpected behaviour emerges which depends crucially on the interactions between individual constituent particles. Such collective behaviour is observed in biological systems, e.g., flocks of birds and schools of fish, and also in the formation of quantum materials such as superfluid helium or superconductors. In quantum systems the collective behaviour can result in the emergence of useful bulk properties such as superfluidity and superconductivity.

Quantum mixtures formed of ultracold atoms provide an extremely clean and well-controlled system for studies of the cooperative behaviour inherent in superfluidity, with exquisite control over interactions, geometry, and rotation (vorticity). In particular, experimental control of interspecies interactions has enabled recent demonstrations of beyond-mean-field phenomena such as quantum droplets and Lee-Huang-Yang gases. Here the net mean-field interactions are significantly reduced such that quantum fluctuations play a dominate role in governing the behaviour of the system. Quantised vortices, topologically-protected defects, are ideal probes of the quantum-many-body state, as their nucleation, internal structure, and dynamics depend directly on the microscopic physics at play. Furthermore, vortices play an integral role in the dissipation of energy in these systems.

I will discuss how vortices may be used to probe binary superfluids and quantum-fluctuation-enhanced regimes, and how this might be implemented experimentally. Within this context, I will also present an overview of the experimental capabilities that I will be developing at the University of Strathclyde to enable studies of vortex dynamics in binary superfluids.

Abstracts of Posters

(in alphabetical order)

Binary Bose-Einstein condensates in a disordered time-dependent potential

Karima Abbas[1,2] **and Abdelaali Boudjemaa**[1,2]

[1]Department of physics, Faculty of Exact Sciences and Informatics, Hassiba Benbouali University of Chlef, P.O. Box 78, 02000, Ouled-Fares, Chlef, Algeria.
[2]Laboratory of Mecanics and Energy, Hassiba Benbouali University of Chlef, P.O. Box 78, 02000, Ouled-Fares, Chlef, Algeria.

We study the non-equilibrium evolution of binary Bose-Einstein condensates in the presence of weak random potential with a Gaussian correlation function using the time-dependent perturbation theory. We apply this theory to construct a closed set of equations that highlight the role of the spectacular interplay between the disorder and the interspecies interactions in the time evolution of the density induced by disorder in each component. It is found that this latter increases with time favoring localization of both species. The time scale at which the theory remains valid depends on the respective system parameters. We show analytically and numerically that such a system supports a steady state that periodically changing during its time propagation. The obtained dynamical corrections indicate that disorder may transform the system into a stationary out-of-equilibrium states. Understanding this time evolution is pivotal for the realization of Floquet condensates.

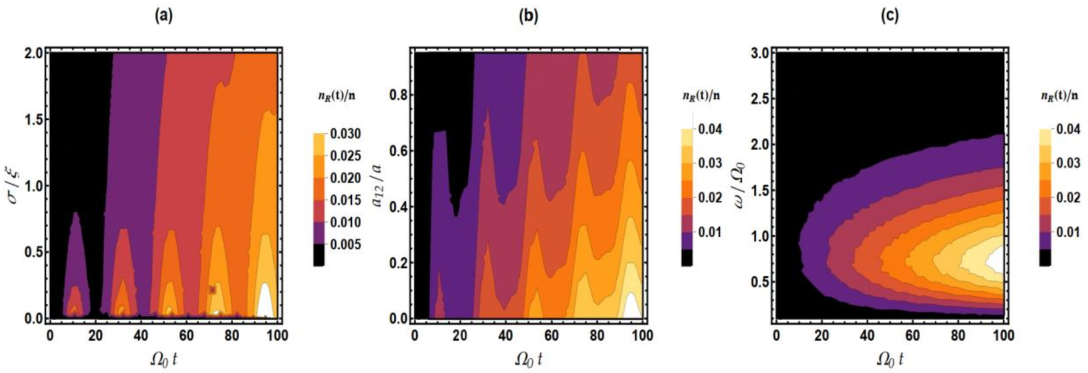


FIG. 3. (Color online) (a) Disorder fraction $n_R(t)/n$ from Eq.(30) as a function of $\Omega_0 t$ and σ/ξ for $a_{12}/a = 0.5$ and $\omega/\Omega_0 = 0.3$. (b) $n_R(t)/n$ as a function of $\Omega_0 t$ and a_{12}/a for $\sigma/\xi = 0.5$ and $\omega/\Omega_0 = 0.3$. (c) $n_R(t)/n$ as a function of $\Omega_0 t$ and ω/Ω_0 for $\sigma/\xi = 1.8$ and $a_{12}/a = 0.5$. Parameters are the same as in Fig.2.

Impurities as probes for quantum phase transition

Ragheed Alhyder

Aarhus University, Physics and Astronomy, Aarhus, Denmark

The realization of accurate measuring devices, which are based on their quantum-mechanical properties, represents a new and exciting research direction with great technological potential. A main goal is to develop atomically sized probes with maximal sensitivity and minimal back action on the environment. Impurity atoms are promising candidates for this, and they have already been used experimentally to measure the temperature and density of a surrounding quantum degenerate gas, as well as to detect induced interactions. Impurities can also be used to probe quantum phase transitions, which can be elusive to detect and characterize experimentally. We have shown in two distinct systems that an impurity atom can be used as a probe for a quantum phase transition. First in a two dimensional Fermi gas across the BKT transition and second in a Bose-Einstein condensate on a lattice across the Mott insulator to Superfluid transition.

Super Bloch oscillations with a parametrically modulated parabolic trap

Usman Ali[1], Martin Holthaus[2] and Torsten Meier[1]

[1] *Paderborn University, Department of Physics, Warburger Strasse 100, D-33098 Paderborn, Germany*

[2] *Institut für Physik, Carl von Ossietzky Universität, D-26111 Oldenburg, Germany*

We study super Bloch oscillations of non-interacting ultracold atoms in a modulated spatially-inhomogeneous system created by the combined potential of a one-dimensional periodic optical lattice and a parabolic trap. Bloch oscillations have been observed for the first-time in real space utilizing the inhomogeneous force provided by a parabolic trap [1]. We see that an external modulation of the trapping potential, with frequency equal to Bloch frequency, give rise to transport and spreading dynamics depending upon the initial phase of the modulation. We find that in the presence of spatial-inhomogeneity the wavepacket transport turn to super Bloch oscillations due to spatially and thus temporally varying Bloch frequency, and in such a setting super Bloch oscillations can be generated in the absence of an external detuning. The reported dynamics are explained by analyzing the time evolution of the wavepacket in real and quasimomentum space, and with the approximate analytical calculations of the group velocity that are compared with numerical results.

References

[1] Z. A. Geiger et al. Observation and Uses of Position-Space Bloch oscillations in an Ultracold Gas. Phys. Rev. Lett. 120, 213201 (2018)

Microcanonical Fluctuations in a Bose-Einstein condensate and its thermal cloud

T. Vibel[1], K. Pawłowski[2], K. Rzążewski[2], M. A. Kristensen[1], J. J. Arlt[1]

[1]*Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C*

[2]*Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02-668 Warsaw*

Quantum systems are typically characterized by the inherent fluctuation of their physical observables. Here we report the characterization of atom number fluctuations in weakly interacting Bose-Einstein condensates. Technical fluctuations are mitigated through a combination of non-destructive detection and active stabilization of the cooling sequence. We observe fluctuations reduced by 27% below the canonical expectation for a non-interacting gas, revealing the microcanonical nature of our system [1]. Similar fluctuations are observed in the thermal cloud, which are closely correlated to the BEC results. This confirms the nature of the fluctuations between the two components of the system. Our experimental results thus set a benchmark for theoretical calculations under typical experimental conditions [2].

References

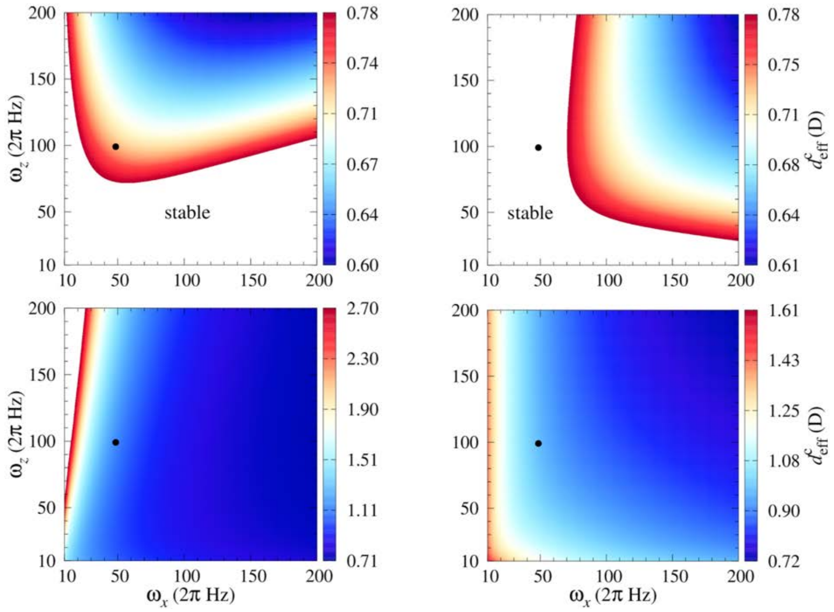
[1] M. B. Christensen et al., Phys. Rev. Lett. **126**, 153601 (2021)
[2] M. B. Kruk et al., arXiv:2207.04536

Stability of quantum degenerate fermionic polar molecules with and without microwave shielding

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

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

A stabilization of a fermionic molecular gas towards collapse in attractive head-to-tail collisions and its evaporative cooling below the Fermi temperature has so far been achieved in two ways. Either a strong dc electric field is applied to confine the molecular motion to 2D [1] or inelastic collisions in 3D are strongly suppressed by applying a circularly polarized microwave field [2]. Here we use a Hartree-Fock mean-field theory [3,4] in order to determine the 3D properties of quantum degenerate fermionic molecules. In particular, we compare the stability diagrams occurring with and without microwave shielding, where a dipole-dipole interaction with negative and positive sign is present. In case when the orientation of the electric dipoles with respect to the trap axes is unknown, we outline how to reconstruct it from time-of-flight absorption measurements.



References

[1] G. Valtolina, et al., Nature **588**, 239 (2020).
[2] A. Schindewolf, et al., Nature **607**, 677 (2022).
[3] V. Veljić, et al., New J. Phys. **20**, 093016 (2018).
[4] V. Veljić, A. Pelster, and A. Balaž, Phys. Rev. Res. **1**, 012009(R) (2019).

Effective potentials in rotating spin-orbit coupled BECs

P. Banger **and S. Gautam**

Indian Institute of Technology Ropar
Rupnagar -140001, Punjab, India

An important research direction opened up in the field of quantum degenerate gases with the experimental realization of artificial gauge fields [1, 2] and spin-orbit (SO) coupling between the spin and the linear momentum of electrically neutral bosons [3]. We theoretically study the stationary-state vortex lattice configurations of rotating spin-orbit- and coherently-coupled spin-1 Bose-Einstein condensates (BECs) in quasi-two-dimensional harmonic potentials [4]. We explore the combined effects of rotation, spin-orbit, and coherent couplings on the spinor system from the single-particle perspective, which is exactly solvable for one-dimensional coupling, under specific coupling and rotation strengths. We illustrate that a boson in these rotating spin-orbit-coupled condensates is subjected to effective toroidal, symmetric double-well, or asymmetric double-well potentials. In the presence of mean-field interactions, using the coupled Gross-Pitaevskii formalism at moderate to high rotation frequencies, the analytically obtained effective potential minima and the numerically obtained coarse-grained density maxima position are in excellent agreement. The effects of rotation are further elucidated by computing the spin expectation per particle for the ferro- and the antiferro-magnetic BECs.

References

[1] Y.-J. Lin, R. L. Compton, K. Jimenez-García, J. V.Porto, and I. B. Spielman Nature **462**, 628 (2009).
[2] Y-J. Lin, R. L. Compton, K. Jiménez-García, W. D.Phillips, J. V. Porto, and I. B. Spielman, Nature Physics **7**, 531 (2011).
[3] Y.-J. Lin, K. Jimenez-García, and I. B. Spielman, Nature **83**, 471 (2011).
[4] C. Wang, C. Gao, C. M. Jian, and H. Zhai, Phys. Rev. Lett. **105**, 160403 (2010)

Pseudo Jahn-Teller Effect in one-dimensional confined fermions

A. Becker[1, 2], G. M. Koutentakis[3] and P. Schmelcher[1, 2]

[1] Center for Optical Quantum Technologies, Department of Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[2] The Hamburg Centre of Ultrafast Imaging, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[3] Insitute of Science and Technology Austria (ISTA), am Campus 1, 3400 Klosterneuburg, Austria

The investigation of the interactions between a few ultracold fermionic atoms provides a tractable way to study fundamental many-body processes in a controllable manner. An important example is symmetry breaking which plays a decisive role in quantum phase transitions. Here, we theoretically unravel such a process, namely the pseudo-Jahn-Teller effect [1] emanating in fermionic heavy-impurity systems. In particular, our variational numerically exact ab-initio Multi-Layer Multi-Configuration Time-Dependent Hartree method for Fermions (ML-MCTDHF) simulations [2] reveal the buildup of entanglement among the impurity and its environment, even in the case of large mass ratios. Detailed comparison of our ML-MCTDHF results with different levels of truncation of the Born-Huang ansatz shows that the main mechanism of this entanglement process is the breaking of the high-level symmetry of the non-interacting system by the influence of the non-adiabatic couplings caused by the interaction among the bath and impurity atoms. Our results can be probed by state-of-the-art ultracold experiments [3,4].

References

1. H. A. Jahn et al., Proc. R. Soc. Lond. Ser. A - Math. Phys. Sc. **161**, 220 (1937)
2. L. Cao et al., J. Chem. Phys. **147,** 044106 (2017)
3. A. N. Wenz et al., Science **342**, 6157 (2013)
4. F. Scazza et al., Phys. Rev. Lett. **118**, 83602 (2017)

Understanding quantum assisted optical activity by narrow band frequency comb using Trichromatic field model

Rita Behera[1,2] and **Swarupananda Pradhan[1,2]**

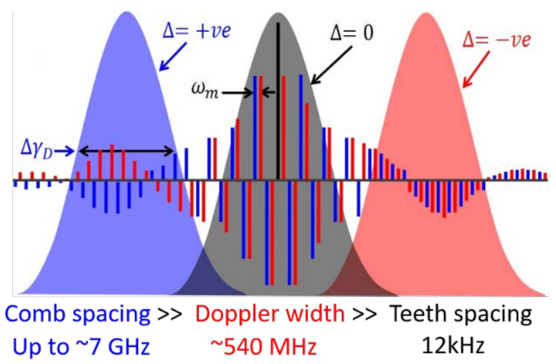
[1]*Homi Bhabha National Institute, Department of Atomic Energy, Mumbai-400094, India*

[2] *Beam Technology Development Group, Bhabha Atomic Research Centre, Mumbai-400085, India*

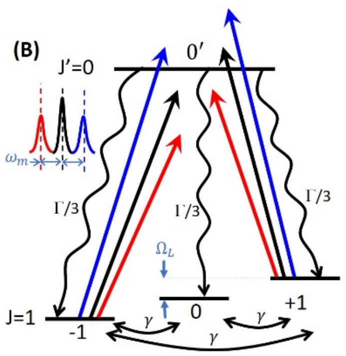
The interaction of narrow band frequency comb (NBFC) with an atomic ensemble near zero magnetic field shows enhanced optical activity at a series of equally spaced Larmor's frequencies. The establishment of quantum interference by multiple frequency components of NBFC followed by optical pumping plays a vital role. The relative phases of the consecutive frequency component further bring complexities to the process. Therefore, for better understanding of the underlying physical process, a trichromatic field model is developed. Only three field are sufficient to epitomize the contribution of large number of frequency components of NBFC as shown in Figure-1. This model utilizes any three consecutive frequency components of NBFC to provide a microscopic picture of the basic mechanism behind the enhancement of optical activity at the multiple Larmor's frequencies. The generalized form of electric field to represent trichromatic field (with phase, φ ,included) is represented as

$$E = -(\cos\epsilon + \sin\epsilon)\left({E_0}^{+} e^{i\varphi_0} + {E_{-1}}^{+} e^{i\varphi_{-1}} e^{i\Omega_m t} + {E_{+1}}^{+} e^{i\varphi_{+1}} e^{-i\Omega_m t}\right) \sigma_+ e^{-i\omega t} + (\cos\epsilon - \sin\epsilon)\left({E_0}^{-} e^{i\varphi_0} + {E_{-1}}^{-} e^{i\varphi_{-1}} e^{i\Omega_m t} + {E_{+1}}^{-} e^{i\varphi_{+1}} e^{-i\Omega_m t}\right) \sigma_- e^{-i\omega t} + c.c$$

The critical role of relative phases among the consecutive frequency component with detuning dependency are also captured by the model. This model successfully explains the dependence of optical activity like absorption, circular birefringence, circular dichroism with various parameters like input field ellipticity, for on- and off-resonant cases etc.



The frequency modulated light can be represented by a series of phase coherent laser modes, termed as NBFC



The complex interaction NBFC (shown in with the atomic ensemble can simplified to the interaction by a tri-chromatic field.

Prethermalization in one-dimensional quantum many-body systems with confinement

<u>Stefan Birnkammer</u>[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, 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 show that in confined systems the thermalization dynamics after a quantum quench instead exhibits multiple stages with well separated time scales. As an example, we consider the confined Ising spin chain, in which domain walls in the ordered phase form bound states reminiscent of mesons. 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. The discussed prethermalization dynamics is directly relevant to generic one-dimensional, many-body systems with confined excitations.

References

1. S. Birnkammer, A. Bastianello, M. Knap, arXiv:2202.12908v1 (2022)

2D supersolid formation in dipolar condensates

T. Bland[1], E. Poli[2], C. Politi[1,2], L. Klaus[1,2], M. A. Norcia[1], F. Ferlaino[1,2], L. Santos[3], and R. N. Bisset[2]

[1]*Institut für Quantenoptik und Quanteninformation (IQOQI), Innsbruck, Austria*
[2]*Institut für Experimentalphysik, University of Innsbruck, Town, Country*
[3]*Institut für Theoretische Physik, Leibniz University Hannover, Germany*

Dipolar condensates have recently been coaxed to form a supersolid phase. While 1D supersolids may be prepared via a roton instability, we find that such a procedure in 2D leads to a loss of both global phase coherence and crystalline order. We develop a finite-temperature stochastic GPE to explore the formation process in 2D, and find that evaporative cooling directly into the supersolid phase – hence bypassing the first-order roton instability – may produce a robust supersolid in a pancake-shaped trap. Importantly, the resulting supersolid is stable at the final nonzero temperature.

Reference

T. Bland, E. Poli, C. Politi, L. Klaus, M. A. Norcia, F. Ferlaino, L. Santos, R. N. Bisset, Physical Review Letters **128**, 195302 (2022)

Alternating-domain supersolids in binary dipolar condensates

T. Bland[1,2], E. Poli[1], L. A. Pena Ardila[3], L. Santos[3], F. Ferlaino[1,2], and R. N. Bisset[1]

[1] *Institut für Experimentalphysik, Universität Innsbruck, Austria*
[2] *IQOQI, Innsbruck, Austria*
[3] *Institut für Theoretische Physik, Leibniz Universität Hanover, Germany*

Two-component dipolar condensates are now experimentally producible, and we theoretically investigate the nature of supersolidity in this system. We predict the existence of a binary supersolid state in which the two components form a series of alternating domains, producing an immiscible double supersolid [1]. Remarkably, we find that a dipolar component can even induce supersolidity in a nondipolar component. In stark contrast to single-component dipolar supersolids, alternating-domain supersolids do not require quantum stabilization [2], and the number of crystal sites is not strictly limited by the condensate populations, with the density hence being substantially lower. Our results are applicable to a wide range of dipole moment combinations, marking an important step towards long-lived bulk-supersolidity.

References

[1] T. Bland *et al.*, arXiv:2203.11119 (2022)
[2] S. Li *et al.*, Phys. Rev. A **105**, L061302 (2022)

Matter-wave lensing of shell-shaped Bose-Einstein condensates

Patrick Boegel[1], Alexander Wolf[2], Matthias Meister[2], and Maxim A. Efremov[1,2]

[1]Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, D-89081 Ulm, Germany

[2] German Aerospace Center (DLR), Institute of Quantum Technologies, D-89081 Ulm, Germany

Motivated by the recent experimental realization of ultracold quantum gases in shell topology, we propose a straightforward implementation of matter-wave lensing techniques for shell-shaped Bose-Einstein condensates. This approach allows to significantly extend the observation time of the condensate shell during its free expansion and enables the study of novel quantum many-body effects on curved geometries. With both analytical and numerical methods, we derive optimal parameters for realistic lensing schemes to conserve the shell shape of the condensate for times up to hundreds of milliseconds.

References

[1] P. Boegel et al. arXiv:2209.04672

Statistically Suppressed Coherence in the Anyon-Hubbard Dimer

M. Bonkhoff[1], A. Pelster[1]
I. Schneider[1] and S. Eggert[1]

1) Physics Department and Research Center Optimas,
Technische Universität Kaiserslautern,
67663 Kaiserslautern, Germany

The impact of statistical transmutation on superfluid tendencies is investigated for the Anyon-Hubbard dimer, a two-site restriction of the lattice generalization of Kundu anyons [1], experimentally accessible via the creation of density-dependent gauge phases and additional strong confinement [2]. We find a duality relation between the anyonic and the Bose-Hubbard dimer, which allows us to construct the corresponding, exact, algebraic Bethe-Ansatz solution. For large particle numbers and weak on-site interactions, the coherence properties are found to be strongly suppressed by statistical transmutation, with underlying mechanisms and applications analogous to one-axis spin-squeezing and entangled coherent states in quantum optics [3,4].

References

[1] Bonkhoff, M. and Jägering, K. and Eggert, S. and Pelster, A. and Thorwart, M. and Posske, T., Phys. Rev. Lett. 126, 163201 (2021)
[2] Frölian, A., Chisholm, C.S., Neri, E. et al., Nature 608, 293–297 (2022)
[3] Kitagawa, M. and Ueda, M., Phys. Rev. A 47, 5138--5143 (1993)
[4] Rice, D. A., Jaeger, G. and Sanders, B. C., Phys. Rev. A 62, 012101 (2000)

Self-bound liquid droplets in a Gaussian-correlated disorder potential

Abdelaali Boudjemaa

Hassiba Benbouali Univeristy, Physics, Chlef, Algeria

We study the effects of Gaussian-correlated disorder potential on self-bound liquid droplets employing the Bogoliubov-Huang-Meng approach.
Useful formulas for the ground-state energy, the equilibrium density, and the disorder fraction of the droplet are selfconsistently derived.
It is shown that for the correlation length is smaller than the healing length, the self-bound droplet breaks into multiple fragments localized the random landscape.
For strong disorder, the droplet evaporates and destroys eventually.

Search for anyonic quasi-particle in a lithium matter-wave microscope

Justus C. Brüggenjürgen[1], Mathis Fischer[1], Luca Asteria[1], Henrik Zahn[1], Marcel Kosch[1], Klaus Sengstock[1], and Christof Weitenberg[1]

[1]*Institut für Laserphysik, Universität Hamburg, 22761 Hamburg, Germany*

Imaging few-body states of ultra-cold atoms requires optical sensitivity on the single atom level. Quantum gas microscopy by pinning atoms in a deep lattice or via free-space methods allows the detection of such states. Here we present matter wave microscopy which uses an intrinsic magnification effect of a wavepaket experiencing two different harmonic confinements or free expansion instead of the second confinement. This enables the resolution of single lattice sites even with rather low-resolution imaging setups as well as a now possible extension of imaging lattice systems in 3D.

In addition, we present a novel lattice setup with highly stable and dynamical control over the lattice geometry. The interference of three lattice beams is suppressed by detuning their frequencies and reestablished by imprinting site-bands onto each beam. The resulting interference pattern is now precisely controllable via the phase differences of those sidebands.

Future prospects of our experiment are single atom detection with a matter wave microscope and few-body state preparation as well as dynamical lattice experiments.

Emergence of damped-localized excitations of the Mott state due to disorder

R. S. Souza[1,2,*], **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 Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany*

[*]*renan@df.ufscar.br*, [†]*axel.pelster@physik.uni-kl.de and* [‡]*santos@ufscar.br*

We present the results summarized in Ref. [1] where we investigate the effect of disorder upon the excitations of the Mott insulating state at zero temperature described by the Bose-Hubbard model. Using the field-theoretical approach developed in Ref. [2] we obtain a resummed expression for the disorder ensemble average of the spectral function. Its analysis shows that disorder leads to an increase of the effective mass of both quasi-particle and quasi-hole excitations. Furthermore, it yields the emergence of damped resonance states, which exponentially decay during propagation in space. We argue that such resonance states correspond to excitations of the Bose-glass phase.

References

[1] R. S. Souza, A. Pelster, and F. E. A. dos Santos arXiv:2209.02435

[2] R. S. Souza, A. Pelster, and F. E. A. dos Santos NJP **23**, 083007 (2021)

Survival of the quantum depletion of a condensate after release from its trap

J. A. Ross, P. Deuar[1], D. K. Shin, K. F. Thomas, B.M. Henson, S. S. Hodgman, A. G. Truscott

[1]Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
[2] Research School of Physics, Australian National University, Canberra, Australia

We present experimental observations and full quantum simulations of the high momentum tail of Bose–Einstein condensates of metastable Helium atoms after release from a magnetic trap [1]. Several features support their interpretation as remnants of the quantum depletion that has "escaped" from its condensate. Surprisingly though, the tails are several times stronger than the in-situ prediction in an equilibrium condensate.

This is in good agreement with a previous experiment [2], in full disagreement with previous theoretical predictions using a simpler model [3], and has an unclear relationship with a more recent experiment in which such tails were found to be empirically correlated with spin impurities [4]. Our experiment, in contrast, does not allow for trapping of such impurity spins. On the other hand, our simulations explain how and why quantum depletion tails can survive expansion, but not at a strength as large as that seen in our experiment. The process(es) underlying the production of these quantum-depletion-like tails therefore remain incompletely explained and intriguing.

References

[1] J. A. Ross *et al.* Scientific Reports **12**, 13178 (2022).
[2] R. Chang *et al.* Phys. Rev. Lett. **117**, 235303 (2016).
[3] C. Qu, L. P. Pitaevskii, S. Stringari, Phys. Rev. A **94**, 063635 (2016).
[4] H. Cayla *et al.* arXiv:2204.10697 (2022).

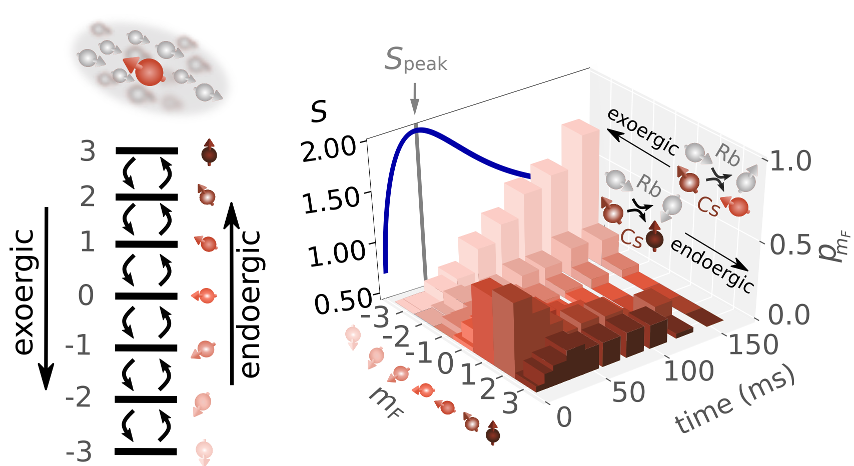
Dynamical phase transition in an open quantum system

Julian Feß,[1] Ling-Na Wu,[2] Jens Nettersheim,[1] Alexander Schnell,[2] Sabrina Burgardt,[1] Silvia Hiebel,[1] Daniel Adam,[1] André Eckardt,[2] and Artur Widera[1]

[1] *Department of Physics and State Research Center OPTIMAS, Technische Universität Kaiserslautern, 67663 Kaiserslautern, Germany*

[2] *Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*

Phase transitions correspond to the singular behavior of physical systems in response to continuous control parameters like temperature. Recently, dynamical quantum phase transitions have been observed in the non-equilibrium dynamics of isolated quantum systems, with time playing the role of the control parameter. However, signatures of such dynamical phase transition in open systems, whose dynamics is driven by the dissipative contact to an environment, were so far elusive. Here, we demonstrate that dynamical phase transitions with respect to time can also occur in open quantum systems described by mixed states. We experimentally measure the relaxation dynamics of the large atomic spin of individual Caesium atoms induced by the dissipative coupling via spin-exchange processes to an ultracold Bose gas of Rubidium atoms. For initial states far from equilibrium, the entropy of the spin state is found to peak in time, transiently approaching its maximum possible value, before eventually relaxing to its lower equilibrium value. Moreover, a finite-size scaling analysis based on numerical simulations shows that it corresponds to a dynamical phase transition of the dissipative system in the limit of large system sizes. Our results show that dynamical phase transitions are not restricted to occur in isolated systems, but, surprisingly, are possible also during the dissipative evolution of open quantum systems.



Stability of a Bose-condensed mixture on a bubble trap

A. Andriati[1], L. Brito[1], L. Tomio[2], and A. Gammal[1]

[1]*Instituto de Física, Universidade de São Paulo, São Paulo-SP, Brazil*
[2]*Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo-SP, Brazil*

Stability and the dynamical behavior of binary Bose-Einstein condensed mixtures trapped on the surface of a rigid spherical shell are investigated at the mean-field level, exploring the miscibility with and without vortex charges and considering repulsive and attractive interactions. To compute the critical points for stability, we follow the Bogoliubov–de Gennes method for the analysis of perturbed solutions, with the constraint that initially the stationary states are in a complete miscible configuration. For the perturbed equal-density mixture of a homogeneous uniform gas and when hidden vorticity is verified, with the species having opposite azimuthal circulation, we consider a small perturbation analysis for each unstable mode, providing a complete diagram with the intra- and interspecies interaction role on the stability of the miscible system. Finally, beyond small-perturbation analysis, we explore the dynamics of some repulsive and attractive interspecies states by full numerical solutions of the time-dependent Gross–Pitaevskii equation.

References

[1] A. Andriati, L. Brito, L. Tomio, and A. Gammal, Phys. Rev. A **104**, 033318 (2021).

N Impenetrable Particles Bouncing on a Mirror: Discrete Time Crystals

W. Golletz[1], A. Czarnecki[2], K. Sacha[1], A. Kuros[1,3]

[1]*Jagiellonian University, Institute of Theoretical Physics, Cracow, Poland*
[2]*Jagiellonian University, Institute of Mathematics, Cracow, Poland*
[3]*Jan Kochanowski University, Institute of Physics, Kielce, Poland*

Spontaneous time-translation symmetry breaking had not attracted much attention until Wilczek [1] introduced the concept of time crystals. Despite this particular realization being prohibited by the “no-go” theorem [2], the idea inspired a new version of time crystals, i.e. the discrete time crystals (DTCs) [3]. In general, a DTC is a periodically driven quantum many-body system that spontaneously breaks the discrete time-translational symmetry of the Hamiltonian due to particle interactions and starts evolving with a period s-times longer than the period of the external driving.

In our previous works, we developed a theoretical basis for the realization of DTCs in the ultra-cold atom platform, i.e. a Bose-Einstein condensate (BEC) of weakly interacting bosonic atoms bouncing resonantly on a periodically driven atom mirror in a 1D space [3-5]. In our present work we take that idea further, and consider a collection of BECs.

Here we will present the first stage of our analysis. It constitutes a classical basis for quantum research of novel time crystal and condensed matter phenomena in the time domain. We consider the dynamics of N impenetrable particles (hard balls) of equal masses stacked above each other in a 1D space. The particles bounce on an oscillating mirror in the presence of gravitational field. We identify the manifolds the particles move on and derive the effective secular Hamiltonian for the resonant motion of the particles. The effective Hamiltonian can be interpreted as describing a fictitious particle in an N-dimensional effective potential (N-dimensional particle) [6].

References

[1] F. Wilczek, Phys. Rev. Lett. **109**, 160401 (2012)
[2] H. Watanabe, and M. Oshikawa, Phys. Rev. Lett. **114**, 251603 (2015)
[3] K. Sacha, Phys. Rev. A **91**, 033617 (2015)
[4] A. Kuros et al., New J. Phys. **22**, 095001 (2020)
[5] K. Giergiel et al., New J. Phys. **22**, 085004 (2020)
[6] W. Golletz et al., New J. Phys. **24**, 093002 (2022)

Interference Induced Anisotropy in 2D Optical Lattices

I. B. Spielman[1], G. Juzeliūnas[2] and E. Gvozdiovas[2]

[1] Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, Maryland, 20899, USA

[2] Institute of Theoretical Physics and Astronomy, Vilnius University, Saulėtekio Ave. 3, LT-10257 Vilnius, Lithuania

Traditionally, optical lattices are created by interfering light beams, trapping atoms at minima or maxima of the emerging interference pattern. However, the resulting potential acting on atoms must follow the structure of the light field. Consequently, the optical trap is limited by diffraction, restricting the characteristic distance over which standard optical lattices can change to be no smaller than half the optical wavelength [1, 2].
In this work we use the Lambda coupling scheme [3, 4, 5] (Fig. 1a) with a control field containing two orthogonal standing waves (one of which is out-of-phase, Fig. 1b) to engineer a two-dimensional optical lattice with sub-wavelength characteristics by means of the geometric phase for the coherent dark state. By using two parameters: 1) the phase difference of the OOF standing wave, and 2) the amplitude ratio of the two orthogonal standing waves, one can control the tunneling parameters. The non-zero phase difference introduces a synthetic magnetic field which can be tuned to realize a weakly interacting tube model.

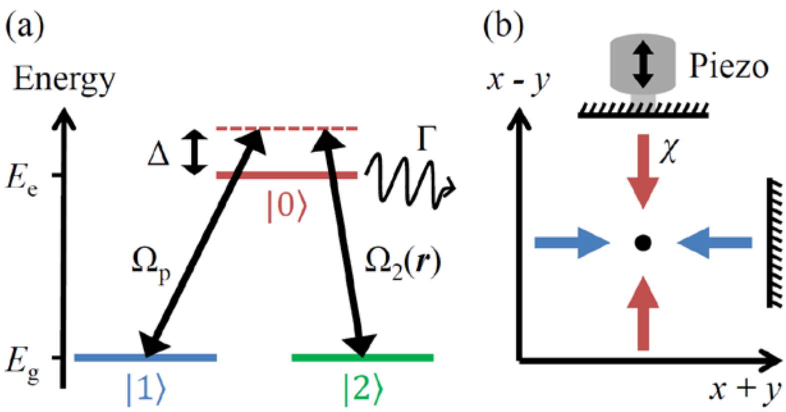


Fig. 1. (a) Lambda coupling scheme. (b) Scheme of the control field $\Omega_2(\boldsymbol{r})$.

References

[1] I. Bloch et al., Reviews of Modern Physics **80**, 885 (2008).
[2] N. Goldman et al., Reports on Progress in Physics **77**, 126401 (2014).
[3] F. Jendrzejewski et al., Physical Review A **94**, 063422 (2016).
[4] M. Łącki et al., Physical Review Letters **117**, 233001 (2016).
[5] Y. Wang et al., Physical Review Letters **120**, 083601 (2018).

Two-dimensional miscible-immiscible supersolid and droplet crystal state in a homonuclear dipolar bosonic mixture

Soumyadeep Halder[1], Subrata Das[1] and Sonjoy Majumder[1]

[1]*Department of Physics, Indian Institute of Technology Kharagpur, kharagpur 721302,India*

The recent realization of binary dipolar BEC [Phys. Rev. Lett. **121**, 213601 (2018)] opens new exciting aspects for studying quantum droplets and supersolids in a binary mixture. Motivated by this experiment, we study groundstate phases and dynamics of a ^{164}Dy-^{164}Dy mixture. Dipolar bosonic mixture exhibits qualitatively novel and rich physics. Relying on the three-dimensional numerical simulations in the extended Gross-Pitaevskii framework, we unravel the groundstate phase diagrams and characterize different groundstate phases. The emergent phases include both miscible and immiscible single droplet (SD), multiple droplets (MD), supersolid (SS), and superfluid (SF) states. More intriguing mixed groundstates may occur for an imbalanced binary mixture, including a combination of SS-SF, SS-MD, and SS-SS phases. Following linear quenches of intra-species scattering lengths across the aforementioned phases, we monitor the dynamical formation of supersolid clusters and droplet lattices. Also, by tuning the inter-species scattering length, we observed the dynamical transition from a miscible MD state to an immiscible MD state with multiple domains formed along the axial direction. Although we have demonstrated the results for a Dy-Dy mixture and for a specific parameter range of intra-species and inter-species scattering lengths, our results are generally valid for other dipolar mixtures and may become an important benchmark for future experimental scenarios.

Instabilities of interacting matter waves in optical lattices with periodic driving.

Matt Mitchell, Robbie Cruickshank, and E. Haller

University of Strathclyde, Glasgow, UK

Periodic driving forces provide a great tool to design complex band structures for ultracold atoms in optical lattices. However, understanding heating mechanisms and the atoms' dynamics in driven lattices is still challenging. We experimentally study the time evolution of weakly and strongly interacting Bose-Einstein condensates of cesium atoms in a 1D optical lattice after a sudden start of the driving. I will provide recent experimental results about parametric and modulational instabilities in those systems.

References

[1] A. Di Carli, et al, Phys. Rev. Lett **127**, 243603 (2022)

Ultracold Fermi Gases in Box Potentials

René Henke

Universität Hamburg

Understanding the origins of unconventional superconductivity has been a major focus of condensed matter physics for many decades. In the past years, quantum simulation with cold atoms has proven to be a valuable platform for studying quantum many-body phenomena, a lot of which closely relate to problems encountered in solid state physics. In our experiment, one important tool are Feshbach resonances, which allow for tuning of the interactions between the individual atoms from a repulsive to an attractive regime. This allows us to access the full crossover from a Bose-Einstein condensate to a Bardeen-Cooper-Schrieffer-type superfluid. Bragg spectroscopy then allows to probe the excitation branches of these systems.

In the past years, our group has managed to build a homogeneous 2D trap for fermionic 6Li, achieve superfluidity and to look into the effects of reduced dimensionality on these systems. Recent works include the observation of the Josephson effect as well as a comparison of the superfluid gap in 2D versus 3D.
This poster will present our way forward towards imbalanced spin mixtures in two dimensions. For these, many questions still remain unanswered, especially regarding the superfluid phase diagram, e.g. whether the phase transition between fully paired superfluid and partially polarized fermi gas is of first or higher order. However, one of the most sought-after phenomenon is the observation of the theoretically predicted but elusive FFLO phase, in which, as a result of the different fermi momentum between spin majority and minority, fermions create pairs with a finite total momentum.

Quantum gases research out of equilibrium-quench

Edward Iraita Salcedo[1], Emmanuel Mercado Gutierrez[1,2], Patricia Castilho Marques[1], Cosme Tancayllo Chacca[1], Pedro Gaspar Minarelli[1], Kilvia Mayre Farias[1] and Vanderlei Salvador Bagnato[1,3]

[1]São Carlos Institute of physics - University of São Paulo, São Carlos, Brazil

[2]Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, USA

[3]Hagler Institute for Advanced Study, Texas A&M University, Texas, USA

Traditionally Bose-Einstein condensate is an equilibrium state with a distribution of population between the ground state and the excited states of an external potential for particles. However, in some situations, modifications can take the system out of the traditional equilibrium. Because the system can thermalize through interactions, returning to the equilibrium situations. The observation of such phenomena can be done through a quantum quench [1-2]. In this process an initial Hamiltonian defined as H(a) has the system in an equilibrium state. Suddenly the Hamiltonian is changed to H(b), and the system finds itself out of the situation of equilibrium of the new Hamiltonian. A time evolution that must occur promotes the system to a new state and the reaching of these new states corresponds to a transient regime. Experimentally, this occurs when we produce abrupt changes in the potential that trap the atoms. In our laboratory, at the research center (CePOF) in São Carlos - Brazil, this quantum quench is performed for sodium atoms, by changing the frequency from 90 rad/sec to 300 rad /sec, followed by the observation of the system during different time intervals. The main result is that our system suffers a quench, producing evolution of the condensate fraction and also the temperature. Preliminary measurements indicate how fast the new equilibrium condition is reached.

References

[1] Eigen, C. *et al*, Nature **563**,221-224 (2018)
[2] Erne, S. *et al*, Nature **563**, 225-229 (2018)

Dissipative time crystals in an atom-cavity platform

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. Moreover, if we modulate the pump of our atom-cavity system periodically we observe discrete time crystalline dynamics [4].

References

[1] F. Piazza and H. Ritsch, *Self-Ordered Limit Cycles, Chaos, and Phase Slippage with a Superfluid inside an Optical Resonator,* PRL, 115, 163601 (2015)

[2] H. Keßler, J. G. Cosme, M. Hemmerling, L. Mathey, and A. Hemmerich, *Emergent limit cycles and time crystal dynamics in an atom-cavity system,* PRA, 99(5), 053605 (2019)

[3] P. Kongkhambut, J. Skulte, L. Mathey, J. G. Cosme, A. Hemmerich, and H. Keßler, *Observation of a continuous time crystal*, Science 307, 6606, 670-673 (2022)

[4] H. Keßler, P. Kongkhambut, C. Georges, L. Mathey, J. G. Cosme, and A. Hemmerich, *Observation of a dissipative time crystal*, PRL 127, 043602 (2021)

Binary supersolids in antidipolar mixtures

Wyatt Kirkby

University of Innsbruck, Institute for Experimental Physics, Innsbruck, Austria

We present a theoretical study of a mixture of antidipolar and nondipolar Bose-Einstein condensates confined to an infinite tube. The long-range antidipolar interaction results in a spin roton which leads to a miscible–to–supersolid phase transition. We present a phase diagram including uniform miscible, supersolid, incoherent domain, and macroscopic domain phases. The low densities of the binary mixture do not require beyond-mean-field quantum fluctuation corrections for stabilization. Our survey ranges from the quasi-1D to the radial Thomas-Fermi (elongated 3D) regimes. We also present the dynamic formation of supersolids following a quench from the uniform miscible phase, which yields phase coherence across the system."

Magnetic processes in Bose Einstein condensates coupled to impurities: state-dressing and Magnetic polarons

G. M. Koutentakis[1], S. I. Mistakidis[2], F. Grusdt[3,4], P. Schmelcher[5,6], and H. R. Sadeghpour[2]

[1]Institute of Science and Technology Austria (ISTA), am Campus 1, 3400 Klosterneuburg, Austria
[2] ITAMP, Center for Astrophysics | Harvard & Smithsonian Cambridge, Massachusetts 02138, USA
[3]Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universitat München, Theresienstr. 37, München D-80333, Germany
[4]Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany
[5]Center for Optical Quantum Technologies, Department of Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
[6]The Hamburg Centre for Ultrafast Imaging, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

We examine the dressing of impurities immersed in Bose-Einstein condensates in the presence of radio-frequency coupling of the underlying spin-states in the cases of a spinor impurity or a spinor BEC. For spinor impurities we identify that polaron generation processes can be controlled in radio-frequency spectroscopy by varying the intensity of the applied pulses as compared to the time-scales of the confining potential and the polaron formation. In particular, for weak pulses the impurity can be driven to a multitude of polaronic states or induce collective modes to the BEC environment, since the injection of the impurity to the polaronic state is adiabatic with respect to the confinement timescale. As the intensity is increased, so that the polaron formation and spin-injection rates become comparable, this multimode structure of the spectrum is replaced by a single resonance corresponding to the polaronic state. The origin of this state can be traced back to the spin-dressing of the impurity which modifies the physical properties of the formed polaron and effectively introduces spin-orbit coupling to the system. In the case of a spinor BEC environment we unveil the formation of the magnetic Bose polaron where the impurity is dressed by magnetic rather than the phononic excitations of its environment. Importantly, this novel quasi-particle under specific conditions can become self-bound into its host, in which case it becomes stable even in the case of strong bath-impurity interactions where the Frőhlich-type Bose polaron has been shown to be unstable. Here we have analyzed the phase-diagram of the system elucidating the emergence of the above mentioned distinct polaron types as the bath-impurity interactions and the radio-frequency coupling are modified and characterize the quasi-particle properties within each particular regime.

Controllable commensurate to incommensurate filling of weakly interacting bosons in 1D

A. La Rooij[1], C. Parsonage[1], L. Koehn[1], A. Di Carli[1], E. Haller[1], S. Kuhr[1]

[1]*Strathclyde University, Glasgow, UK*

Quantum gas microscopes have the unique ability to study ultracold atoms in optical lattices with single-site resolution. Using dynamic control of a local repulsive trapping potential by means of a digital micromirror device, we are able to prepare 1D systems with a fixed small number of lattice sites. By creating a Mott insulating state in between these repulsive potential barriers, we initialise the system with a well-controlled number of bosonic atoms. After driving the system into a superfluid state, we move the projected potential barriers inwards or outwards. This changes the number of available lattice sites while maintaining the atom number, thus changing the system from being commensurate to an incommensurate situation. The incommensurate system that has features of a weak-superfluid state while for commensurate systems we observe the onset of the MI transition by measuring on-site atom number and variance.

We also briefly present a method to create holographic light potentials using a phase-shifting spatial light modulator. Using precise wavefront detection, camera feedback and modelling of the pixel crosstalk, we are able to reduce the rms errors of the potentials to below 2%. We further present a study in which we compare three different deconvolution techniques to reconstruct the atomic lattice occupation, using simulated quantum-gas microscope images of single atoms in an optical lattice. Using a local iterative deconvolution algorithm, Wiener deconvolution and the Lucy-Richardson deconvolution algorithm, we investigate which deconvolution method is best capable of resolving the atomic lattice occupation as a function of signal-to-noise ratio, lattice filling, imaging resolution and lattice spacing.

References

[1] Preprint at arxiv: 2207.08663

Tunable diffusion properties of spin-polarized Fermi gases in time-dependent disorder

F. Lang[1], S. Barbosa[1], J. Koch[1], and A. Widera[1]

[1]*Physics Department and State Research Center OPTIMAS, Technische Universität Kaiserslautern, Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany*

The transport of particles through disordered potential landscapes has been actively studied for the last decades. The majority of these studies, e.g. of Anderson localization, addressed the regime in which the disordered potential is static. However, it seems natural to investigate the influence of time-dependent disorder on transport properties. More specifically, a crossover from localization to diffusive, even hyper-ballistic, transport is expected to occur when the disorder varies in time. We experimentally investigate the dynamics of ultracold, spin-polarized fermionic lithium atoms when exposed to such a time-dependent optical speckle potential. Here, we observe a strong dependence of the system's diffusion exponent on the so-called correlation time, a measure for the speckle's variation rate.

Collective excitation in quantum droplets of Bose-Bose mixture

Avra Banerjee, Saswata Sahu, and Dwipesh Majumder
Department of Physics, Indian Institute of Engineering Science and Technology, Shibpur, W B, India
Email: *avrabanerjee1@gmail.com, sahu.saswata@gmail.com, dwipesh@physics.iiests.ac.in*

We have studied the collective excitation of Bose-Einstein condensate of short-range weak interacting atoms with spin-orbit coupling (SOC) in two dimensions in the liquid phase. We solved the Gross-Pitaevskii equation to get the droplet's ground state of the condensate. We have included Rashba, Dresselhaus SOC, and Raman SOC in our study. The study of Bogoliubov excitation shows that in small interactions, only phonon modes are present, and for higher interactions, roton modes start to appear. Energy spectra contain two roton modes in the relatively strong interacting atomic system. In addition to the two-dimensional system, we have studied the collective excitations of the droplet of the Bose-Bose atomic mixture inside a Rydberg atom. In this lecture, I shall briefly describe the method of calculation and the results. The change of roton minima due to the SOC interaction and Rydberg atomic electronic interaction is exciting. In addition to bulk excitation, we have studied the surface mode of collective excitation. To study the surface mode, we have considered the spherical droplet and solved the matrix-eigenvalue problem numerically. We have shown the effect of Rydberg electron interaction on the surface mode.

References:

1. S. Sahu, D. Majumder; Collective excitation of two-dimensional Bose–Einstein condensate in liquid phase with spin–orbit coupling, *J. Phys. B* **53**, 095301 (2020).
2. S. Sahu, D. Majumder; Two-dimensional interacting Bose–Bose droplet in random repulsive potential, *Euro. Phys. J. Plus* **137,** 1020(2022).

Impurity physics with Bose-Einstein condensates

Andreas Morgen[1]

[1]Center for Complex Quantum Systems, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark

Spectroscopic and interferometric measurements complement each other in extracting the fundamental properties of quantum many-body systems. While spectroscopy provides precise measurements of equilibrated energies, interferometry can reveal the evolution of the system. For an impurity immersed in a bosonic medium, they allow for a complete understanding the quasiparticle physics of the Bose polaron. Comparing the interferometric and spectroscopic timescales to the underlying dynamical regimes of the impurity dynamics and the polaron lifetime, highlights the capability of the interferometric approach to clearly resolve polaron dynamics. Furthermore, interactions between impurities mediated by the bath have been theorized to result in a bound state, known as the bipolaron. Using different spectroscopic methods we have investigated this state. Our results give a comprehensive picture of the many-body physics governing the Bose polaron and thus validate the quasiparticle framework for further studies.

References

[1] Magnus G. Skou, Kristian K. Nielsen, Thomas G. Skov, Andreas M. Morgen, Nils B. Jørgensen, Arturo Camacho-Guardian, Thomas Pohl, Georg M. Bruun and Jan J. Arlt. arXiv:2204.01424 (2022)

[2] Andreas M. Morgen et al. „Mediated interactions in strongly interacting BEC“. In preparation

Nonequilibrium hole dynamics in antiferromagnets: damped strings and polarons

K. Knakkergaard Nielsen[1,2], T. Pohl[2] and G. M. Bruun[2,3]

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

[2] *Department of Physics and Astronomy, Aarhus University, Ny Munkegade, 8000 Aarhus C, Denmark*

[3] *Shenzhen Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology, Shenzhen 518055, China*

We develop a nonperturbative theory for hole dynamics in antiferromagnetic spin lattices [1], as described by the t-J model. This is achieved by generalizing the self-consistent Born approximation to nonequilibrium systems, making it possible to calculate the full time dependent many-body wave function. Our approach reveals three distinct dynamical regimes, ultimately leading to the formation of magnetic polarons. Following the initial ballistic stage of the hole dynamics, coherent formation of string excitations gives rise to characteristic oscillations in the hole density. Their damping eventually leaves behind magnetic polarons that undergo ballistic motion with a greatly reduced velocity. The developed theory provides a rigorous framework for understanding nonequilibrium physics of defects in quantum magnets and quantitatively explains recent observations from cold-atom quantum simulations [2] in the strong coupling regime.

References

[1] K. Knakkergaard Nielsen et al., arXiv:2203.04789 (2022)
[2] G. Ji et al., Phys. Rev. X **11**, 021022 (2021)

Pattern formation on quantum droplet in the presence of quasi-periodic optical lattice

Maitri R. Pathak[1] *and Ajay Nath*[1]
[1]*Indian Institute of Information Technology Vadodara, Gandhinagar, Gujarat 382 028, India*
E-mail: 201773002@iiitvadodara.ac.in

Pattern formation has always been topic of discussion, from observing ensemble of birds flying in sky, dropping pebbles in water and such order are reported in the quantum system like dipolar quantum gas [1], quantum ferrofluids [2], chemical and biological systems etc [3]. Exploration of pattern formation and out of equilibrium dynamics on the quantum fluids especially on quantum droplets has been very less explored area with many open questions yet to be answered. The same has been done here on new class of quantum fluid known as quantum droplet. We have subjected our study on quantum droplet under the influence of driven quasi periodic bi-chromatic optical lattice (BOL). Utilizing extended Gross Pitaevskii equation, we construct an exact analytical model for investigating the phenomenon of pattern formation in driven BOL. We consider condensate dynamics in the following experimental scenario: (a) dc driven BOL, (b) ac driven BOL and (3) ac modulated driven and tilted BOL. It has been observed that such driven system results into formation of pattern on quantum droplet and transition from droplet to soliton is also illustrated.

Reference:

[1] Chomaz, L. et al. Long-lived and transient supersolid behaviors in dipolar quantum gases. Phys. Rev. X 9, 021012 (2019).

[2] Kadau, H. et al. Observing the Rosensweig instability of a quantum ferrofluid. Nature 530, 194–197 (2016).

[3] Maini, P. K., Painter, K. J. & Chau, H. N. P. Spatial pattern formation in chemical and biological systems. J. Chem. Soc. Faraday Trans. 93, 3601–3610 (1997).

Quantum mechanical description of thermo-optic interaction in photon BECs

Enrico Stein and Axel Pelster

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

Photon Bose-Einstein condensates are created in a dye-filled microcavity. This confinement freezes out the longitudinal motion, mapping the photons to a two-dimensional gas of massive bosons. The dye solution continually absorbs and re-emits these photons, causing the photon gas to thermalise and to form a Bose-Einstein condensate. Because of a non-ideal quantum efficiency, these cycles heat the dye solution, creating a medium that provides an effective photon-photon interaction. However, so far only a zero-temperature description of this process exists [1].

Therefore, this poster presents a description of the effective photon-photon interaction, which includes explicitly the thermal cloud [2]. An Exact Diagonalisation approach exposes how the effective photon-photon interaction modifies both the spectrum and the width of the photon gas [3]. In particular, the Exact Diagonalisation turns out to be crucial for understanding the dimensional crossover from 2D to 1D [4], as here larger photon-photon interactions may occur [5]. A comparison with a variational approach based on the Gross-Pitaevskii equation quantifies the contribution of the thermal cloud in the respective applications.

References

[1] E. Stein, F. Vewinger, and A. Pelster, New J. Phys. **21**, 103044 (2019).
[2] E. Stein and A. Pelster, arXiv:2203.16955 (2022).
[3] E. Stein and A. Pelster, arXiv:2204.08818 (2022).
[4] E. Stein and A. Pelster, New J. Phys. **24**, 023013 (2022).
[5] E. Stein and A. Pelster, New J. Phys. **24**, 023032 (2022).

Thermalization of photons in InGaAs/GaAs quantum wells and in VCSELs

M. Pieczarka[1], M. Gębski[2], A. Piasecka[1], P. Wyborski[1], A. Broda[3], I. Sankowska[3], J. Muszalski[3] and T. Czyszanowski[2]

[1]Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland
[2]Photonics Group, Institute of Physics, Lodz University of Technology, Łódź, Poland
[3]Łukasiewicz Research Network − Institute of Microelectronics and Photonics, Warsaw, Poland

Photons - the first-ever considered particles to follow the Bose-Einstein statistics. Surprisingly, photon gases were one of the latest to show signatures of Bose-Einstein condensation, besides many analogies developed over the years in laser physics. Recently, semiconductor lasers have been argued to be a promising direction in the Bose-Einstein condensation of photon gases at room temperature [1].

Here, we test the possibility of utilizing a vertical-cavity surface-emitting laser (VCSEL) as a platform for studying photon thermalization and Bose-Einstein condensation. Firstly, we test the device's active region, performing temperature-dependent resonant photoluminescence excitation spectroscopy (PLE) measurements to verify the degree of thermal equilibrium radiation in the system. It is done by verifying the Kennard-Stepanov relation in the sample [2], see Figure. We found a perfect match of the temperatures above 70 K, proving the thermalization of the carriers and light in this sample. We further probe the thermalization of photons in the full VCSEL sample with the same QWs as an active region and look for signatures of Bose-Einstein condensation in experiments using nonresonant optical excitation and using electrically driven, fully fabricated devices.

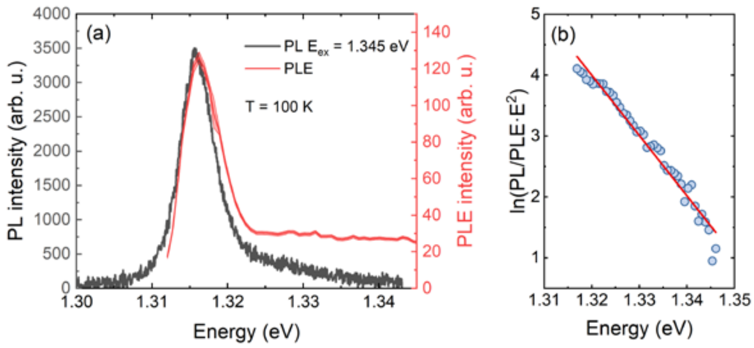


Figure (a) PL and PLE spectra of the QW sample taken at 100 K. (b) Kennard-Stepanov law verification, where the linear fit yields a spectral temperature of about 100 K.

References

[1] S. Barland, et al., Opt. Express **29**, 8368 (2021)
[2] T. Ihara, et al., Phys. Rev. B **80**, 033307 (2009)

Out of equilibrium dynamical properties of Bose-Einstein condensates in ramped up weak disorder

M. Radonjić[1,2], R. P. A. Lima[3,4], and A. Pelster[4]

[1] *I. Institute of Theoretical Physics, University of Hamburg, Hamburg, Germany*
[2] *Institute of Physics Belgrade, University of Belgrade, Belgrade, Serbia*
[3] *GISC and GFTC, Instituto de Física, Universidade Federal de Alagoas, Maceió AL 57072-970, Brazil*
[4] *Physics Department and Research Center OPTIMAS, Technical University of Kaiserslautern, Kaiserslautern, Germany*

We investigate theoretically how the superfluid and the condensate deformation of a weakly interacting ultracold Bose gas evolve during the ramping up of an external weak disorder potential. Both resulting deformations turn out to consist of two distinct contributions, namely a reversible equilibrium one, already predicted by Huang and Meng in 1992 [1,2], as well as a non-equilibrium dynamical one, whose magnitude depends on the details of the ramping protocol [3]. For the specific case of the exponential ramping up protocol, we are able to derive analytic time-dependent expressions for the aforementioned quantities. After sufficiently long time, the steady state emerges that is generically out of equilibrium. We make the first step in examining its properties by studying the relaxation dynamics into it. Also, we investigate the two-time correlation function and elucidate its relation to the equilibrium and the dynamical part of the condensate deformation.

References

[1] K. Huang and H.-F. Meng, Phys. Rev. Lett. **69**, 644 (1992)
[2] B. Nagler, M. Radonjić, S. Barbosa, J. Koch, A. Pelster, and A. Widera, New J. Phys. **22**, 033021 (2020)
[3] M. Radonjić and A. Pelster, SciPost Phys. **10**, 008 (2021)

Conformal Duality of Bose-Einstein condensates with two- and three-body interactions

D. Reinhardt[1], M. Meister[1], D. Lee[2] and W. P. Schleich[3]

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

[2] *Michigan State University, Facility for Rare Isotope Beams and Department of Physics and Astronomy, East Lansing, Michigan, USA*

[3]*Institute of Quantum Physics, Ulm University, Ulm, Germany*

It is well known that the stationary solutions for quantum systems with contact interaction (e.g. Bose-Einstein condensates (BECs) described by the Gross-Pitaevskii equation (GPE)) differ from those of the linear Schrödinger equation (LSE) [1], [2]. For instance, solitons only occur for nonlinear systems.

Moreover, the solutions change when including three-body interaction (or higher interactions terms) in addition to the standard two-body interactions usually considered [3].

To examine the different solution spaces, we treat both equations in the hydrodynamic frame, resulting in a first order differential equation for the two-body density and three-body density, respectively. Both differential equations are polynomic in the density with cubic (two-body-case) and quartic (three-body-case) dependence.

References

[1] L. D. Carr, C. W. Clark, and W. P. Reinhardt, “Stationary solutions of the one-dimensional nonlinear Schrödinger equation. I. Case of repulsive nonlinearity,” Phys. Rev. A, vol. 62, p. 063610, (2000).

[2] L. D. Carr, C. W. Clark, and W. P. Reinhardt, “Stationary solutions of the one-dimensional nonlinear Schrödinger equation. II. Case of attractive nonlinearity,” Phys. Rev. A, vol. 62, p. 063611, (2000).

[3] H. Schürmann, “Traveling-wave solutions of the cubic-quintic nonlinear Schrödinger equation,” Phys. Rev. E, vol. 54, p. 4312, (1996).

Probing relaxation dynamics of few strongly correlated bosons in 1D triple well optical lattice

S. Bera[1] , R. Roy[1] , A. Gammal[2] , B. Chakrabarti[1,2] and B. Chatterjee[3]

[1]Department of Physics, Presidency University, 86/1 College Street, Kolkata 700073, India
[2] Instituto de Física, Universidade de São Paulo, CEP 05508-090, São Paulo, Brazil
[3]Department of Physics, Indian Institute of Technology-Kanpur, Kanpur 208016, India

We prepare a few-body system of three bosons in three well optical lattices and the relaxation process of the repulsively interacting bosons is studied from the first principle using the multiconfigurational time-dependent Hartree method for bosons (MCTDHB). We observe a contrasting response of the system under two independent quench processes: an interaction quench and a lattice depth quench. We analyze the evolution of the reduced one-body density matrix, two-body density and the Shannon information entropy for a wide range of lattice depth and interaction strength parameters. For strong interaction quench, we observe a very fast relaxation to the steady state. In contrast, for lattice depth quench, we observe collapse-revival dynamics in all the key measures. We define t_{relax} and $t_{revival}$, two characteristic time when the system relaxes to another state or the time when the system revive back to initial state. We also provide the best fitting formulas for relaxation and revival time which follow power law decay.

References

[1] S. Bera, R. Roy, A. Gammal, B. Chakrabarti, B. Chatterjee, J. Phys. B **52**, 21 (2019)

[2] R. Roy, A. Gammal, M. C. Tsatsos, B. Chatterjee, B. Chakrabarti and A. U. J. Lode, Phys. Rev. A **97**, 043625 (2018)

Poster title: Bose-Einstein Condensation on Curved Manifolds

Author: Natália Salomé Móller

Abstract: The simplest shapes that serves as a model to the bubble-trap are spheres and ellipsoids. However, experiments are never perfect, and the best surface that would describe the bubble-trap could be a complicated manifold. In order to deal with such generality, we study a Bose-Einstein Condensation confined on general smooth manifolds [N S Móller *et al* 2020 *New J. Phys.* **22** 063059]. We perform a dimensional reduction, assuming that the confinement frequency in the normal direction to the manifold is large enough so that we can extremize the action, and integrate out the normal degree of freedom to the manifold. We end up with a quasi-two dimensional Gross Pitaevskii equation and the cloud width is defined self-consistently. For the special case of a sphere, we compute low-lying collective excitations together with their eigenfrequencies, determining how such quantities depend on the interaction strength. We find the existence of two families of oscillation modes, where one of them happens predominantly on the surface of the sphere and the other family happens predominantly on the cloud thickness. Finally, for a general geometry, we analyse two kind of two-dimensional effective potentials. We show that one of then happens due to external asymmetries of the confinement potential, while the other one is intrinsically due to the curvature of the shell. Moreover, on an ellipsoid, we show that these potentials have different profiles.

Creation and robustness of quantized vortices in a dipolar supersolid when crossing the superfluid-to-supersolid transition

M. Šindik,[1,2] A. Recati,[1,3] S. M. Roccuzzo,[4] L. Santos,[5] and S. Stringari[1,3]

[1]INO-CNR BEC Center and Department of Physics, University of Trento, Italy
[2]Institute of Physics Belgrade, University of Belgrade, Serbia
[3]Trento Institute for Fundamental Physics and Applications, INFN, Italy
[4]Kirchhoff-Institute for Physics, Ruprecht-Karl University of Heidelberg, Germany
[5]Institute for Theoretical Physics, Leibniz University Hannover, Germany

Experiments on dipolar Bose-Einstein condensates have recently reported the observation of supersolidity. Although quantized vortices constitute a key probe of superfluidity, their observability in dipolar supersolids is largely prevented by the strong density depletion caused by the formation of droplets. We present a novel approach to the nucleation of vortices and their observation, based on the quenching of the s-wave scattering length across the superfluid-supersolid transition. Starting from a slowly rotating, vortex-free, configuration in the superfluid phase, we predict vortex nucleation as the system enters the supersolid phase, due to the strong reduction of the critical angular velocity in the supersolid. Once a vortex is created, we show that it is robustly preserved when the condensate is brought back to the superfluid phase, where it may be readily observed.

Dynamical phases in an atom-cavity system: From time crystals to dark states

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

[3]National Institute of Physics, University of the Philippines, Diliman, Quezon City 1101, Philippines

Ultracold atoms placed inside a high finesse optical cavity, which are continuously pumped or periodically driven display very rich phase diagrams. We specifically discover non-equilibrium phases called time crystals. Time crystals are classified as discrete or continuous depending on whether they spontaneously break discrete or continuous time translation symmetry.

First, we study an emergent limit cycle phase for a blue-detuned pump and show that the phase of the oscillations are random for different realizations, hence this dynamical many-body state spontaneously breaks continuous time translation symmetry. We present the robustness of this state against temporal noise and its stability in the limit of large particle numbers, classifying this state as a continuous time crystal [1]. On the other hand, if we periodically drive the amplitude of the pump field, we find a period doubling response, which can be *in-situ* observed from the light phase of the cavity photons. This state corresponds to a dissipative time crystal [2,3]. Finally, phase shaking of the pump beam can lead to an incommensurate time crystal [4]. The non-integer subharmonic oscillatory motion corresponds to dynamical switching between symmetry-broken states, which are nonequilibrium bond ordered density wave states. We map the system onto a parametrically driven dissipative three-level Dicke model [5] and present the experimental realization [6]. For strong driving, we further show that this state is only metastable and relaxes into a dark state. We show that this stationary subradiant state, with respect to the pump lattice, can be understood as a Bose-Einstein condensate excited to the second Bloch band with an order parameter composed of p-orbitals with staggered local phases [7].

Employing a semiclassical phase-space representation for the dissipative quantum dynamics, we confirm the rigidity and persistence of the various time crystalline phases, namely the continuous, dissipative, and incommensurate time crystals, as well as the dark state.

References

1. P. Kongkhambut, J. Skulte et al., Science **377**, 670 (2022)
2. H. Keßler, P. Kongkhambut et al., PRL **127**, 043602 (2021)
3. R. J. L. Tuquero, J. Skulte et al., PRA **105,** 043311 (2022)
4. J. G. Cosme, J. Skulte, and L. Mathey, PRA **100**, 053615 (2019)
5. J. Skulte, P. Kongkhambut et al., PRA **104**, 063705 (2021)
6. P. Kongkhambut, H. Keßler et al., PRL **127**, (2021)
7. J. Skulte, P. Kongkhambut et al., arXiv:2209.03342 (2022)

Self-oscillating pump in a topological dissipative atom–cavity system

D.Dreon[1], A.Baumgärtner[1], X.Li[1], S.Hertlein[1], J.Stefaniak[1], T.Esslinger[1] and T.Donner[1]

[1]*Institute for Quantum Electronics, Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland*

Pumps are transport mechanisms in which direct currents result from a cyclic evolution of the potential. As Thouless showed, the pumping process can have topological origins, when considering the motion of quantum particles in spatially and temporally periodic potentials. However, the periodic evolution that drives these pumps has always been assumed to be imparted from outside, as has been the case in the experimental systems studied so far. Here we report on an emergent mechanism for 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. Owing to dissipation, the cavity field evolves between its two quadratures, each corresponding to a different centrosymmetric crystal configuration[1]. This self-oscillation results in a time-periodic potential analogous to that describing the transport of electrons in topological tight-binding models, such as the paradigmatic Rice–Mele pump. In the experiment, we directly follow the evolution by measuring the phase winding of the cavity field with respect to the driving field and observing the atomic motion in situ. The observed mechanism combines the dynamics of topological and open systems, and features characteristics of continuous dissipative time crystals.

References

1. Li, X. et al. First order phase transition between two centro-symmetric superradiant crystals. *Phys. Rev. Res.* **3**, L012024 (2021).

Mixed Bubbles in a one-dimensional Bose-Bose mixture

P. Sturmer, M. Nilsson Tengstrand. S. M. Reimann

[1] *IMathematical Physics and NanoLund, Lund University, Box 118, 22100 Lund, Sweden*

We investigate a Bose-Bose mixture across the miscible-immiscible phase transition governed by quantum fluctuations in one dimension. We find the recently predcited [1] so-called ‘mixed bubbles’ as ground states close to the mean field miscible-immsicible threshold. These bubbles form a pocket of miscibility, separated by one of the components. The collective excitations reflect the symmetry breaking resulting from the bubble formation. The partial miscibility of the system allows for persistent currents in an annular confinement. Intriguingly, the mixed bubble acts like an intrinsic weak link, connecting the rotational behavior of the mixed bubble state to current efforts in atomtronic applications.

References

[1] P. Naidon and D.S. Petrov, Phys. Rev. Lett. **126**, 115301 (2021)

Josephson-type oscillation in a spin-orbit coupled Bose-Einstein Condensate in the presence of nonlinear optical lattices

Sumaita Sultana[1*] and G.A.Sekh[1]

[1] Department of physics, Kazi Nazrul University, Asansol, India

*E-Mail: reach2sumaita@gmail.com

We consider spin orbit coupled Bose Einstein condensate in presence of linear and nonlinear optical lattices within the framework of quasi-one- dimensional Gross-Pitaevskii equation. The effects of coupling are primarily identified by the dispersion curve through the appearance of single and double minima. It basically creates two pseudospin states with equal or different momenta. The atomic population imbalance between these states executes Josephson-type(JT) oscillation. We examine the effects of optical lattice on that oscillation dynamics. It is seen that the nonlinear optical lattice increases amplitude of the JT oscillation and also changes the phase. The population imbalance is associated with some interesting dynamics of the center-of-mass of the system. We find an effective potential for the center-of-mass and check how the optical lattices interplay to control the dynamics of center of mass motion and hence to influence the JT dynamics.

References:

[1] F.Kh. Abdullaev et al, Physical Review A **97**,053611(2018)

[2] H. Sakaguchi and Boris A. Malomed, Phys. Rev. E **72**,046610(2009)

[3] Sumaita Sultana and G.A.Sekh Josephson-type oscillation in a spin-orbit coupled Bose-Einstein condensate in the presence of nonlinear optical lattices.(**Under preparation**).

Particle and heat transport of a unitary fermi gas through a dissipative quantum point contact

M. Talebi[1], P. Fabritius[1], J. Mohan[1], S. Wili[1], M. Huang[1], and T. Esslinger[1]

[1]Department of Physics, ETH Zürich, 8093 Zürich, Switzerland

We investigate the effect of spin-selective particle dissipation on the transport of a fermionic superfluid. We prepare a unitary Fermi gas of lithium-6 atoms in a two-reservoir geometry connected via a quantum point contact (QPC). On the one hand, the relaxation of particle imbalance between the reservoirs manifests itself in a non-linear current-bias relation, which can be understood with multiple Andreev reflections (MAR) [1]. On the other hand, an initial temperature imbalance leads to a particle current reaching a non-equilibrium steady state (NESS) which is the evidence of the violation of the Wiedemann-Franz law in the unitary gas [2]. In this experimental work, we apply a spin-selective resonant beam localized at the QPC and observe its influence on the transport initiated by particle or temperature imbalance respectively. In the first case, we show that the non-linear current-bias relation is smoothly connected to a linear, Ohmic transport as the dissipation increases. Moreover, we confirm this finding theoretically using the Keldysh formalism [3]. In the second case, we observe that the dissipation results in the destruction of the NESS at long transport times for all regimes of dissipation strength. However, at short transport times, we observe an overshoot of the particle-imbalance response compared to the NESS at weak dissipation strength. The overshoot peak shows a non-monotonic behavior as dissipation increases, from an enhancement of the response to a suppression compared to the NESS. We model this problem using a phenomenological linear model and find that, surprisingly, the non-monotonic behavior can result from a monotonic change in thermoelectric parameters. Our work opens new perspectives of dissipation engineering of particle and heat transport in strongly interacting systems.

References

[1] D. Husmann, S. Uchino, S. Krinner, M. Lebrat, T. Giamarchi, T. Esslinger, and J. P. Brantut, Science **350**, 1498 (2015)

[2] D. Husmann, M. Lebrat, S. Häusler, J. P. Brantut, L. Corman, and T. Esslinger, P. N. A. S. **115**, 8563 (2018)

[3] M. Huang, J. Mohan, A. M. Visuri, P. Fabritius, M. Talebi, S. Wili, S. Uchino, T. Giamarchi, and T. Esslinger, arXiv: 2210.03371 (2022)

Vortex flow and quantum turbulence generated in stirred mass-imbalanced Bose-Einstein condensed mixtures

A. N. da Silva[1], L. Tomio[1], R. K. Kumar[2] and A. S. Bradley[2]

[1] *Instituto de Física Teórica, Universidade Estadual Paulista, 01140-070 São Paulo, SP, Brazil*
[2] *Department of Physics, Centre for Quantum Science, and Dodd-Walls Centre for Photonic and Quantum Technologies, University of Otago, Dunedin 9054, New Zealand.*

We report a study on the dynamical production of stable vortices and quantum turbulence, with binary mass-imbalanced atomic mixtures, confined by a pancake-like trap perturbed by a time-dependent stirring interaction [1]. For that, we consider the coupled species of ^{85}Rb-^{133}Cs and ^{85}Rb-^{87}Rb, within miscible configurations. In order to distinguish turbulent from non-turbulent flows, we study the time evolution of the incompressible kinetic energy contributions of both species. In the transient turbulent regime, before stable vortex patterns are produced, the characteristic $k^{-5/3}$ Kolmogorov behavior is clearly identified for both species at intermediate momenta k above the inverse Thomas-Fermi radial positions, further modified by the universal k^{-3} scaling at momenta higher than the inverse of the respective healing lengths. A relevant outcome is verified that the dynamical production of stable vortices occurs much faster for larger mass differences in the binary mixture.

References

[1] A.N. da Silva, R. Kishor Kumar, A. S. Bradley, L. Tomio, *Vortex generation in stirred binary Bose-Einstein condensates*, arXiv:2205.14654.

Self-bound fermionic mixtures in 1D

J. Givois[1] , A. Tononi[1], and D. S. Petrov[1]

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

Self-binding in Bose-Bose mixtures has received lots of experimental and theoretical attention in the recent years, and a few studies discussed also Bose-Fermi droplets [1]. Fermi-Fermi mixtures with interspecies attraction, however, are not expected to display self-bound states, since the fermions of one species should overcome a strong Pauli pressure to bind the fermions of the other. This repulsion is, in fact, the fundamental mechanism that provides stability of Fermi mixtures along the BCS-BEC crossover, whose dimers repel and do not form larger clusters [2].

In our recent work [3], surprisingly, we find that one-dimensional Fermi-Fermi mixtures with sufficiently large mass imbalance can form a self-bound state in the thermodynamic limit. This result elaborates our previous few-body analyses [4], and is based on a mean-field theory in which the heavy fermions are described within the Thomas-Fermi approximation, which is exact in the limit of large mass ratios. Our work sets the basis for future studies of self-bound fermions in higher-dimensional cases, which can shed light on the fundamental behavior of macroscopic fermionic aggregates.

References

[1] D. Rakshit, et al., Self-bound Bose–Fermi liquids in lower dimensions, New J. Phys. 21, 073027 (2019); T. Karpiuk, et al., Bistability of Bose–Fermi mixtures, New J. Phys. 22, 103025 (2020).

[2] D. S. Petrov, C. Salomon, and G. V. Shlyapnikov, Weakly bound dimers of fermionic atoms, Phys. Rev. Lett. 93, 090404 (2004).

[3] J. Givois, A. Tononi, and D. S. Petrov, Self-binding of one-dimensional fermionic mixtures with zero-range interspecies attraction, arXiv:2207.04742.

[4] A. Tononi, J. Givois, and D. S. Petrov, Binding of heavy fermions by a single light atom in one dimension, Phys. Rev. A 106, L011302 (2022).

Excitations of a dipolar Tonks-Girardeau droplet

Buğra Tüzemen[1],

[1])Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland
btuzemen@cft.edu.pl

The stabilization of the ultracold Bose gas due to the quantum corrections has resulted in observance and thorough analysis of the droplet state. We focus on attractive dipolar systems with strong contact repulsion in quasi-1D geometry. To this end, we utilize the framework known as the Lieb-Liniger Gross Pitaevskii equation, which is more reliable for strong contact interactions.

We investigate the properties of dark solitons in dipolar Bose gas with strong contact interactions and whether they can coexist with the droplet state. Our studies show that as the dipolar interaction strength γ_{dd} reaches a critical value, the motionless black soliton's width diverges logarithmically, making it easily detectable in experiments. As γ_{dd} increases, the dark solitons stay stable up to a second critical γ_{dd}. Interestingly, now the black soliton has a finite density. Furthermore, we confirm a coexistence between the dark soliton and the droplet rather than a split by calculating the fidelity between the numerically evaluated phase-imprinted state and the solitonic solution.

We also study the Bogoliubov excitation modes of TG droplets. Our study focuses mainly on the regime of infinite contact repulsion and tight transversal harmonic confinement, where there are analytic formulas for the density profiles. Moreover, we propose a simplified analytical ansatz suitable to work outside this regime, provided the gas is in the deep flat-top region of density profiles.

Finally, we study the Bose gas with strong contact repulsion and non-local dipolar attraction on a lattice. We employ the extended Bose-Hubbard Hamiltonian. We generate three solutions: gas, liquid, and self-bound Mott insulator (bMi), then we quench the strong repulsion to strong attraction. Expectedly, we observe no change in the gas and bMi, but surprisingly, the liquid state shows an expansion.

Dissipative dynamics of an impurity with spin-orbit coupling

Areg Ghazaryan[1], Alberto Cappellaro[1], Mikhail Lemeshko[1], and A.G. Volosniev[1]

[1]*Institute of Science and Technology Austria (ISTA), am Campus 1, 3400 Klosterneuburg, Austria*

Brownian motion of a mobile impurity in a bath is affected by **spin-orbit coupling** (SOC). We discuss a **Caldeira-Leggett-type** model that can be used to propose and interpret quantum simulators of this problem in **cold Bose gases** [1]. First, we derive a master equation that describes the model and explore it in a one-dimensional (1D) setting. To validate the standard assumptions needed for our derivation, we analyze available experimental data without SOC; as a byproduct, this analysis suggests that the quench dynamics of the impurity is beyond the 1D Bose-polaron approach at temperatures currently accessible in a cold-atom laboratory – motion of the impurity is mainly driven by dissipation. For systems with SOC, we demonstrate that 1D spin orbit coupling can be 'gauged out' even in the presence of dissipation – the information about SOC is incorporated in the initial conditions. Observables sensitive to this information (such as spin densities) can be used to study formation of steady spin polarization domains during quench dynamics.

References

[1] A. Ghazaryan, A. Cappellaro, M. Lemeshko, A. Volosniev: arXiv:2210.01829

QRydDemo - A Rydberg Atom Quantum Computer Demonstrator

Jiachen Zhao[1], P. Ilzhöfer[1], G. Unnikrishnan[1], R. K. Gupta[1], J. Krauter[1], A. Scholz[1], S. Weber[2], H. P. Büchler[2], S. Montangero[3], S. Stuhler[4] T. Pfau[1] and F. Meinert[1]

[1] 5th Institute of Physics, University of Stuttgart, Germany
[2] Institute for Theoretical Physics III, University of Stuttgart, Germany
[3] Department of Physics and Astronomy 'G. Galilei', University of Padova, Padova, Italy
[4] TOPTICA Photonics AG, 82166 Gräfelfing, Germany

Quantum computing is attracting great interest due to its potential for solving computationally hard problems. A variety of platforms like superconducting circuits, trapped ions or neutral atoms are under investigation to achieve a quantum computational speedup utilizing a large number of qubits and combined with a high-fidelity universal gate set. A comparatively young and very dynamically developing platform in terms of scalability and gate fidelity utilizes trapped neutral atoms excited to Rydberg states. The QRydDemo project aims to build a quantum computer based on neutral strontium atoms individually trapped in an optical tweezer array. We will study a so far unexplored qubit encoded in the $^3P_0$ and $^3P_2$ finestructure states of Strontium. This qubit provides "triple magic trapping" and the potential to improve the coherence time by a factor of 1000 from previous demonstrations of 10 microseconds to 10 milliseconds[1]. We will combine this qubit with a novel tweezer architecture which allows for reshuffling of the qubits during the quantum computation. Such a dynamically adjustable qubit array allows for new algorithmic possibilities by effectively increasing the connectivity for deep quantum circuits to solve real-world problems.

[1] F. Meinert, T. Pfau, C. Hölzl, EU Patent Application No. EP20214187.5

*jzhao@pi5.physik.uni-stuttgart.de

Approaching practical quantum computational advantage using ultracold atoms

Y.-G. Zheng[1, 2, 3], W.-Y. Zhang[1, 2, 3], Y.-C. Shen[1, 2, 3], A. Luo[1, 2, 3], Y. Liu[1, 2, 3], M.-G. He[1, 2, 3], H.-R. Zhang[1, 2, 3], W. Lin[1, 2, 3], H.-Y. Wang[1, 2, 3], Z.-H. Zhu[1, 2, 3], M.-C. Chen[1, 2, 3], C.-Y. Lu[1, 2, 3], S. Thanasilp[4], D. G. Angelakis[4, 5], Z.-S. Yuan[1, 2, 3] and J.-W. Pan[1, 2, 3]

[1]Hefei National Research Center for Physical Sciences at the Microscale and School of Physical Sciences, USTC, Hefei 230026, China
[2]CAS Center for Excellence in Quantum Information and Quantum Physics, USTC, Hefei 230026, China
[3]Hefei National Laboratory, USTC, Hefei 230088, China
[4]CQT, NUS, 3 Science Drive 2, Singapore 117543
[5]School of Electrical and Computer Engineering, Technical University of Crete, Chania, Greece 73100

Nonequilibrium dynamics of quantum many-body systems is challenging for classical computing [1,2], providing opportunities for demonstrating practical quantum computational advantage with analogue quantum simulators [3]. Due to the intimate connection with a random matrix ensemble, it is proposed to be classically intractable to sample the driven thermalized many-body states of a Bose-Hubbard system [4], and further extract multi-point correlations from the output-strings for characterizing quantum systems [5]. Here, leveraging dedicated precise manipulations and atom-number-resolved detection through a quantum gas microscope with bichromatic superlattices, we implement and sample the driven Hubbard chains in the thermalized phase involving up to 32 sites with 20 atoms. In this regime, the estimated effective computational power of sampling in our quantum simulator is comparable to that of the fastest supercomputer with currently known best algorithms. We employ the Bayesian tests to verify that our prepared systems operate in the driven thermalized phase. Multi-point correlations of up to 14th-order extracted from the experimental samples offer clear distinctions between the thermalized and many-body-localized phases. Our work [6] paves the way towards practical quantum computational advantage applied in simulating Floquet dynamics of many-body systems [3].

References

[1] R. P. Feynman, Int. J. Theor. Phys. **21**, 467–488 (1982).
[2] J. Preskill, arXiv:1203.5813.
[3] A. J. Daley, et al., Nature **607**, 667–676 (2022).
[4] S. Thanasilp, et al., Phys. Rev. B **103**, 165132(2021).
[5] T. Schweigler, et al., Nature **545**, 323–326 (2017).
[6] Y.-G. Zheng, et al., arXiv:2210.08556.

Universal Hall response and flavour-selective localization in strongly interacting lattice fermions

T.-W. Zhou[1], D. Tusi[2], L. Franchi[1], J. Parravicini[1,2,3], G. Cappellini[2,3], M. Inguscio[4,2,3], J. Catani[2,3], and L. Fallani[1,2,3]

[1]*Department of Physics and Astronomy, University of Florence, 50019 Sesto Fiorentino, Italy*
[2]*European Laboratory for Non-Linear Spectroscopy (LENS), 50019 Sesto Fiorentino, Italy*
[3]*Istituto Nazionale di Ottica del Consiglio Nazionale delle Ricerche (CNR-INO), Sezione di Sesto Fiorentino, 50019 Sesto Fiorentino, Italy*
[4]*Department of Engineering, Campus Bio-Medico University of Rome, 00128 Rome, Italy*

We report on the first quantum simulation of the Hall effect for strongly interacting fermions [1]. By performing direct measurements of current and charge polarization in an ultracold-atom simulator, we trace the buildup of the Hall response [2] in a synthetic ladder pierced by a magnetic flux, going beyond stationary Hall voltage measurements in solid-state systems. We witness the onset of a clear interaction-dependent behavior, where the Hall response deviates significantly from that expected for a non-interacting electron gas, approaching a universal value. Our system, able to reach hard to compute regimes also demonstrates the power of quantum simulation for strongly correlated topological states of matter.

We also report on the first observation of flavour-selective localization in an atom-based quantum simulator [3]. Our experiment realizes Fermi-Hubbard models with an SU(3) symmetry that can be broken using a tunable coupling between flavours [4]. We observe an enhancement of localization associated with selective Mott transition, and the emergence of flavour-dependent correlations. Our realization of flavour-selective Mott physics demonstrates the potential of cold atoms to simulate interacting multicomponent materials such as superconductors and topological insulators.

References

[1] T.-W. Zhou et al., arXiv:2205.13567 (2022)
[2] S. Greschner et al., PRL **122**, 083402 (2019)
[3] D. Tusi et al., Nature Physics **18**, 1201 (2022)
[4] L. Del Re et al., PRA **98**, 063628 (2018)