Book of Abstracts

FINESS 2018

Finite Temperature Non-equilibrium Superfluid Systems

19-23 February 2018

Wanaka, New Zealand

The Dodd-Walls Centre for Photonic and Quantum Technologies

OPTIMAS TU Kaiserslautern

FLEET ARC Centre of Excellence in Future Low-Energy Electronics Technologies

CTCP

Centre for Quantum Science University of Otago

BTG

	Monday	Tuesday	Wednesday	Thursday	Friday
8 AM	8.45 - 8.50 -	Welcome 8.45am	Quantum World 8.40		
9 AM	9.30 -	Ott	Gasenzer	Anderson	Parish
		Davis	Blakie	Simula	Hoinka
					Glazman
10 AM	10.10 -	Mark	Prüfer	Neely	Kjaergaard
	10.30 -	Andersen	Takeuchi	Helmerson	Morning Tea
	10.50 -				
11 AM	11.30 -	Morning Tea 10.50am—11.30am	Morning Tea	Morning Tea	Gardiner
		Gross	Cugliandolo	Shin	
12 PM	12.10 -				Proukakis
		Demler	Deuar	Fleischhauer	
	12.50 -				Lunch
1 PM	1.10 -	Poletti	Lunch/Excursion 12.50pm — 6pm	Pelster	
		Lunch 1.10pm—2.30pm		Lunch	
2 PM	2.30 -	Snoke		Zoller	
3 PM	3.10 -	Szymanska		Rey	
	3.50 -	Afternoon Tea 3.50pm—4.30pm		Afternoon Tea	
4 PM	4.30 -	Ostrovskaya		Jaksch	
5 PM	5.10 -	Mitra		Svistunov	
	5.50 -				
6 PM	Meet and Greet 6pm — 8pm		Poster Session 6pm-8pm	Banquet 6.30pm—10pm	
7 PM					

- 10.30
- 11.10
- 11.50
- 12.30
- 2.00

Welcome Information

It is a great pleasure to welcome you to Wanaka New Zealand for FINESS 2018!

Wifi An access code for the Edgewater wifi is given at the registration desk.

News Announcements will be aggregated on the FINESS website (Twitter #FINESS2018).

Talks (Summit Room) Invited talks are 35min + 5mins questions. Hot topic talks are 15min + 5mins questions. You can plug in your laptop, or upload your talk. Please check in with your session chair and confirm that your talk displays prior to the commencement of your session. The projector resolution is 1920×1080.

Poster Session (Pavillion) Please set up your poster on Wednesday before the end of morning tea (11.30am). Due to banquet setup, posters will need to be removed prior to the start of the first session on Thursday morning.

Lunch Lunch will be in the Pavillion Tuesday-Thursday. On Friday lunch will be served in the Summit Room.

Banquet Drinks and canapes will be served from 6:00pm. Seating at 6:45pm.

Book Launch The official launch of

The Quantum World of Ultra-Cold Atoms and Light Book III: Ultra-Cold Atoms,
Crispin Gardiner and Peter Zoller, World Scientific

will occur on Wednesday 21 February, at 8.40-8:50am in the Summit Room.

Local Organisers
Ashton Bradley (Chair)
Danny Baillie
Joachim Brand
David Hutchinson
Diana Evans

International Advisory Panel
Andrew Daley (Chair)
Ana Maria-Rey
Matthias Troyer
Immanuel Bloch
Simon Gardiner
Marzena Szymanska
Thomas Gasenzer
Michael Fleischhauer
Nick Proukakis
Luis Santos

Contents

Talk Abstracts

Tuesday 20th February

Open Bose-Einstein Condensates

Invited
20 Feb
8:50am

Herwig Ott
Department of Physics, University of Kaiserslautern, Germany

Ultracold quantum gases are usually well isolated from the environment. This allows for the study of ground state properties and non-equilibrium dynamics of many-body quantum systems under almost ideal conditions. Introducing a controlled coupling to the environment "opens" the quantum system and non-unitary dynamics can be investigated. Such an approach provides new opportunities to study fundamental quantum phenomena and to engineer robust many-body quantum states.

I will present an experimental platform [1,2] that allows for the controlled engineering of dissipation in ultracold quantum gases by means of localized particle losses. This is exploited to study quantum Zeno dynamics in a Bose-Einstein condensate [3], where we find that the particle losses are well described by an imaginary potential in the system's Hamiltonian. We also investigate the steady-states in a driven-dissipative Josephson array [4]. For small dissipation, the steady-states are characterized by balanced loss and gain and the eigenvalues are real. This situation corresponds to coherent perfect absorption, a phenomenon known from linear optics. Above a critical dissipation strength, the system decays exponentially, indicating the existence of purely imaginary eigenvalues.

[1] T. Gericke et al., Nature Physics 4, 949 (2008).
[2] P. Würtz et al., Phys. Rev. Lett. 103, 080404 (2009).
[3] G. Barontini et al., Phys. Rev. Lett. 110, 035302 (2013).
[4] R. Labouvie et al. Phys. Rev. Lett. 116, 235302 (2016).

Invited
20 Feb
9.30am

Non-equilibrium phase transition and bistability in a driven-dissipative superfluid

M T Reeves and M J Davis
ARC Centre of Excellence for Future Low-Energy Electronics Technologies, School of Mathematics and Physics, University of Queensland, Australia

Interacting systems driven far from equilibrium have a tendency to spontaneously self organise. The non-equilibrium steady states which emerge from this process often exhibit exotic properties that cannot be achieved near equilibrium. In the context of many-body quantum systems, exploiting such behaviour can offer controlled manipulation and preparation of many-body quantum states, by introducing engineered sources of driving and dissipation.

In a recent experiment, Labouvie et al. studied a driven-dissipative Josephson junction array realised with a Bose-Einstein condensate (BEC) residing in a one-dimensional optical lattice [1]. A focussed electron beam caused dissipation at a single lattice site, while tunnelling from neighbouring sites provided driving. The system was observed to exhibit bistability - supporting states of either superflow and resistive flow across the junction depending on the initial condition. Critical slowing down was also observed in the dynamics, suggestive of a non-equilibrium phase transition.

We develop a minimal model of this system within the framework of c-field theory [2], where the system site of interest is a pancake shaped BEC described via a stochastic Gross-Pitaevskii equation subject to coherent driving. In contrast to previously considered Hubbard-type models, the c-field model exhibits the key qualitative behaviours of the system, suggesting a feasible route to quantitative modelling of such complex non-equilibrium quantum systems.

[1] R. Labouvie, B. Santra, S. Heun, and H. Ott, Physical Review Letters 116, 235302 (2016).
[2] P. B. Blakie, A. S. Bradley, M. J. Davis, R. J. Ballagh and C. W. Gardiner, Advances in Physics 57, 363 (2008).

Hot Topic
20 Feb
10:10am

Observation of the roton mode in a dipolar quantum gas

Manfred Mark
Institut für Experimentalphysik, Universität Innsbruck, and Institut für Quantenoptik und Quanteninformation, Innsbruck, Austria

The concept of a roton, a special kind of elementary excitation, forming a minimum of energy at finite momentum, has been essential to understand the properties of superfluid 4He. In the realm of highly controllable quantum gases, a roton mode has been predicted to emerge due to dipolar interparticle interactions despite of their weakly interacting character [1]. Yet it has remained elusive to observations. Here we report measurements of the momentum distribution of dipolar quantum gases of highly-magnetic erbium atoms, revealing the existence of the long-sought roton. The population of the roton mode is induced by performing a controlled quench of the interaction strength in the quantum gas. When the dominantly dipolar regime is reached, we observe the appearance of reproducible symmetric peaks at a well-defined momentum matching the inverse of the tight confinement length as expected for dipolar rotons. By modifying the trap geometry and the interaction parameters, we investigate further the special properties of the roton mode. Our combined theoretical and experimental work [2] demonstrates unambiguously the roton softening of the excitation spectrum in axially elongated dipolar quantum gases and provides a further step in the quest towards supersolidity emerging from the intrinsic interparticle interactions.

[1] L. Santos et al., Phys. Rev. Lett. 90, 250403 (2003).
[2] L. Chomaz et al., arxiv:1705.06914.

Hot Topic
20 Feb
10:30am

Spin-dynamics in a Two-atom Gas

Mikkel F. Andersen
Dodd-Walls Centre, University of Otago

Spin exchange collisions between atoms provide an efficient route for generation of entanglement in ultra-cold few- and many-body systems as well as an avenue for exploring fundamental physical phenomena such as for example quantum magnetism. Studying microscopic processes at the individual event level reveals interesting phenomena that is otherwise concealed in ensemble-average measurements. We study spin dynamics of individually prepared pairs of spin-2 atoms colliding in a tightly confining optical tweezers. The two-atom gas is at finite temperature and both atoms are initially prepared in the $m = 0$ state. The observed m-state population evolution shows near perfect correlation between the m-levels of the two atoms on time scales exceeding a second. When the atoms have left the $m = 0$ state, we observe a relative number fluctuation between their spin states 11.91 ± 0.3 dB below quantum shot noise (QSN), limited only by finite detection efficiency. Contrary, to both finite temperature many-body experiments and ultra-cold two-body experiments, we observe spin relaxation dynamics to thermal equilibrium populations of the relevant two-body spin states. Our work may provide a route for robust generation of entanglement at finite temperature.

Invited
20 Feb
11:30am

Microscopic Studies of Many-Body Localization in Two Dimensions

Christian Gross
Max Planck Institute of Quantum Optics

The breakdown of the thermalization of a generic isolated quantum system is one consequence of many-body localization. This aspect can be probed experimentally in systems of ultracold lattice atoms by the measurement of the long-time remaining traces of an initially prepared far from equilibrium distribution of the atomic density. We summarize our experiments performed in this spirit and report on recent progress on the characterization of the system in the seemingly localized phase, including the study of the stability of the localization when coupling to a well controlled atomic bath.

Invited
20 Feb
12:10pm

Superconducting Higgs laser

Eugene Demler
Harvard University

Electromagnetic properties of superconductors with excited Higgs mode will be considered. It will be shown that such systems can exhibit optical amplification. Implications for pump and probe experiments will be discussed.

Hot Topic
20 Feb
12:50pm

Interplay of interaction, disorder and a tailored bath

Dario Poletti
Singapore University of Technology and Design

The interplay between interaction and dissipation can induce interesting out-of-equilibrium phase transitions and can be used for state engineering. One natural question is: how robust are these states against disorder? At the same time, interaction and disorder can induce many body localization: how robust is this against a tailored bath which counters disorder? Here we study the interplay between disorder, interaction and a tailored bath and show the sensitivity of dissipatively engineered states to disorder and study signatures of localization.

[1] Xu, Guo, Poletti, arxiv:1709.08934

Invited
20 Feb
2:30pm

Equilibration of a polariton condensate in a quasi-1D ring trap

David Snoke
University of Pittsburgh

We have succeeded at making quantum wires for polaritons which allow long distance propagation around the ring (hundreds of microns) and lifetime of the polaritons long enough to thermalize. A gradient of the potential energy in a ring geometry produces a trap with a rigid pendulum Hamiltonian. In this system we see oscillations of the polariton condensate at the natural frequency of the pendulum, and the onset of coherence in the condensate, which depends on the density of the particles. We also see evidence for spin phase separation in the trap. Analysis of the detailed dynamics allows us to extract a very accurate value of the polariton-polariton interaction cross section.

Polariton quantum fluids in and out of equilibrium

Invited
20 Feb
3:10pm

Marzena Szymanska
University College London

State-of-the-art semiconductor microcavities allowed recently to achieve a fully thermalised photonic system analogous to cold atoms or liquid Helium. Here, we predict and observe the Berezinskii-Kosterlitz-Thouless transition for a 2D gas of exciton-polaritons with its clear signature in the first-order coherence both in space and time. We show that the mechanism of pairing of the topological defects (vortices) is responsible for the transition to the algebraic order and achieve a thermodynamic equilibrium phase transition in an otherwise open driven/dissipative system [1].

At the same time, it has been shown that driven-dissipative polariton fluid could potentially exhibit a truly novel non-equilibrium order, where superfluidity is accompanied by stretched exponential decay of correlations. This celebrated Kardar-Parisi-Zhang (KPZ) phase has not been achieved in any physical system in 2D and even 1D realisations are not conclusive. We show that driven microcavity polaritons in the OPO configuration can act as a natural and unifying laboratory for the exploration of a variety of intrinsic non-equilibrium phenomena, including the so far experimentally elusive KPZ phase in two dimensions [2]. Key features are the high tuneability of microscopic parameters in general, and of the spatial anisotropy of the microscopic physics in particular.

[1] D. Caputo, D. Ballarini, G. Dagvadorj, C. Sánchez Muõz, M. De Giorgi, L. Dominici, K. West, L. N. Pfeiffer, G. Gigli, F. P. Laussy, M. H. Szymanska, D. Sanvitto, "Topological order and thermal equilibrium in polariton condensates", Nature Materials 17, 145 (2018).
[2] A. Zamora, L. M. Sieberer, K. Dunnett, S. Diehl, and M. H. Szymanska, "Tuning across Universalities with a Driven Open Condensate", Phys. Rev. X 7, 041006 (2017)

Exciton-polariton condensate in a box

Invited
20 Feb
4:30pm

Elena Ostrovskaya
The Australian National University

Non-resonant optical excitation of exciton polaritons in semiconductor microcavities is a versatile technique for creating Bose-Einstein condensates of exciton polaritons in an effective pump-induced trapping potential. In the single-shot, pulsed regime of the spontaneous exciton-polariton condensation, the effective trapping potential is created by a non-stationary, photo-injected excitonic reservoir and is therefore strongly affected by the depletion process. By utilising this experimental regime, we create high-density, spatially uniform exciton-polariton condensates in a reservoir-induced "round box" potential. This enables us to apply the Thomas-Fermi approximation and estimate the strength of polariton-polariton interactions, which has been subject to considerable debate in the exciton-polariton community.

Invited
20 Feb
5:10pm

Transport in transient superfluids

Aditi Mitra
New York University

Recent advances in ultra-fast measurement in cold atoms, as well as pump-probe spectroscopy of K_3C_{60} films, have opened the possibility of rapidly quenching systems of interacting fermions to, and across, a finite temperature superfluid transition. However determining that a transient state has approached a second-order critical point is difficult, as standard equilibrium techniques are inapplicable. We show that the approach to the superfluid critical point in a transient state may be detected via time-resolved transport measurements, such as the optical conductivity. We leverage the fact that quenching to the vicinity of the critical point produces a highly time dependent density of superfluid fluctuations, which affect the conductivity in two ways. Firstly by inelastic scattering between the fermions and the fluctuations, and secondly by direct conduction through the fluctuations. The competition between these two effects leads to non-monotonic behavior in the time-resolved optical conductivity, providing a signature of the critical transient state.

Wednesday 21st February

Universal dynamics - from Bose fields to spin networks

Invited
21 Feb
8:50am

Thomas Gasenzer
Heidelberg University, Germany

Quantum many-body systems far from equilibrium show much richer characteristics than those in equilibrium. There is the possibility for universal dynamics, showing up with the same properties in very different systems irrespective of their concrete building blocks. Examples which are being studied intensely at present are the phenomenon of prethermalisation [1] and of superfluid turbulence. Non-thermal fixed points have been proposed on the grounds of the Schwinger-Keldysh approach to non-equilibrium quantum field theory. These lead beyond standard equilibrium universality and are characterized by different anomalous scaling dimensions [2,3]. I will briefly summarize the status of the theory on universal semi-classical dynamics after a quench and furthermore shed some light on the relation between the build-up of long-range correlations, quantum entanglement entropy, and neural network representations of spin systems [4].

[1] T. Langen, T. Gasenzer, and J. Schmiedmayer, JSTAT 064009, 2016. arXiv:1603.09385.
[2] I. Chantesana, A. Piñeiro Orioli, and T. Gasenzer, "Kinetic theory of non-thermal fixed points in a Bose gas", arXiv:1801.to appear (30/01/2018).
[3] M. Karl and T. Gasenzer, New J. Phys. 19: 093014, 2017; arXiv:1611.01163 (2016).
[4] S. Czischek, M. Gärttner, et al., 2018 (to appear)

Phase ordering of a ferromagnetic spin-1 condensate

Invited
21 Feb
9:30am

Blair Blakie
Dodd Walls Centre and Department of Physics, University of Otago

An area of interest in many-body systems involves the dynamics induced by a quench across a phase transition to a symmetry-broken phase. Following the quench domains form with each making an independent choice for the symmetry-breaking order parameter. An important aspect involves how these domains coarsen over time (phase ordering) as the different broken-symmetry phases compete to select the equilibrium state. Often at late times the coarsening is universal: correlation functions of the order parameter collapse to a universal function when scaled by a characteristic length $L(t)$, where t is the time after the quench.

In this talk I will examine the dynamics of a quasi-two-dimensional spin-1 condensate quenched into a ferromagnetic phase and demonstrate that the late time coarsening is universal [1,2]. A feature of spin-1 condensates is that the order parameter symmetry is dependent upon the value of the quadratic Zeeman energy, allowing us to explore regimes where the magnetic order is easy-plane, easy-axis or isotropic. In each case the ordering dynamics is different as is the relevant topological defects.

[1] L.A. Williamson and P.B. Blakie, Phys. Rev. Lett.119, 255301 (2017).
[2] L.A. Williamson and P.B. Blakie, Phys. Rev. Lett. 116, 025301 (2016).

Hot Topic
21 Feb
10:10am

Observation of universal dynamics in an isolated quantum system

Maximilian Prüfer
Heidelberg University

After a quench a non-integrable many-particle system will eventually relax back to its thermal state. However, on the route to thermalisation universal dynamics characterised by temporal rescaling of spatial correlation functions may be encountered, a phenomenon known as a non-thermal fixed point. We access and study this regime both experimentally and theoretically for a Bose-Einstein condensate of ^{87}Rb in the $F = 1$ hyperfine manifold with ferromagnetic interactions. We prepare our system in the polar phase and quench into the symmetry-broken ferromagnetic phase. After a build-up of excitations in the transversal spin we observe self-similar evolution, which is due to the non-linear redistribution of excitations among different momenta. We determine the emerging scaling form for the structure factor of the transversal spin and extract the set of corresponding scaling exponents. Our results give access to universal properties of the non-linear dynamics beyond the prethermalisation stage of the relaxation process.

Hot Topic
21 Feb
10:30am

Application of percolation theory to coarsening dynamics of domains in segregating binary superfluids

Hiromitsu Takeuchi
Osaka City University

The domain-area distribution in the phase transition dynamics of Z_2 symmetry breaking is studied theoretically and numerically for segregating binary Bose–Einstein condensates in quasi-two-dimensional systems. Due to the dynamic scaling law of the phase ordering kinetics, the domain-area distribution is described by a universal function of the domain area, rescaled by the mean distance between domain walls. The scaling theory for general coarsening dynamics in two dimensions hypothesizes that the distribution during the coarsening dynamics has a hierarchy with the two scaling regimes, the microscopic and macroscopic regimes with distinct power-law exponents.The power law in the macroscopic regime, where the domain size is larger than the mean distance, is universally represented with the Fischer's exponent of the percolation theory in two dimensions. On the other hands, the power-law exponent in the microscopic regime is sensitive to the microscopic dynamics of the system. This conjecture is confirmed by large-scale numerical simulations of the coupled Gross–Pitaevskii equation for binary condensates. In the numerical experiments of the superfluid system, the exponent in the microscopic regime anomalously reaches to its theoretical upper limit of the general scaling theory.

The anomaly comes from the quantum-fluid effect in the presence of circular vortex sheets, described by the hydrodynamic approximation neglecting the fluid compressibility. It is also found that the distribution of superfluid circulation along vortex sheets obey a dynamic scaling law with different power-law exponents in the two regimes. An analogy to quantum turbulence on the hierarchy of vorticity distribution and the applicability to chiral superfluid ^{3}He in a slab are also discussed.

Thermal quenches in the stochastic Gross-Pitaevskii equation: morphology of the vortex network

Invited
21 Feb
11:30am

Leticia F. Cugliandolo
Sorbonne Université, Laboratoire de Physique Théorique et Hautes Energies

A system taken across a second order phase transition from its disordered into its symmetry-broken phase undergoes a phase ordering process. Topological defects are left in the system at finite times after the quench and, in open systems, they are gradually eliminated in the course of evolution towards equilibrium.

After briefly summarising results obtained some years ago on the slow quench of the 2d XY model, I will discuss a recent detailed study of the evolution of 3d weakly interacting bosons at finite chemical potential, taken across their phase transition, using the stochastic Gross-Pitaevskii equation. In short, I will explain the full characterisation of the vortex network in and out of equilibrium. This is work in collaboration with Michikazu Kobayashi (Kyoto University).

A classical field theory free of the curses of ultraviolet divergence and cutoff dependence

Invited
21 Feb
12:10pm

Piotr Deuar
Institute of Physics, Polish Academy of Sciences

A c-field description of ultracold interacting Bose gases has been constructed that does not suffer from the UV divergence catastrophe and is amenable to both equilibrium states and dynamics. Predictions converge to asymptotic values as the energy cutoff grows and the numerical lattice becomes finer, while the occupation of high energy modes follows the Bose-Einstein distribution. The computational efficiency scales the same way as standard classical field methods. To achieve this, an SGPE-like reservoir coupling is mustered to act as a constraint on the high-energy part of the system. The key to avoiding the UV divergence is then to preserve the quantum properties of the constraining reservoir. Examples in 1d and 3d will be given, including the troublesome $m = 0$ collective quadrupole mode of a trapped gas that has previously eluded accurate description with c-fields. For dynamics, a "Bose-Einstein edge" can be implemented, such that modes with energy above this level remain Bose-Einstein distributed, while those below are free to evolve as in standard classical fields. This protects the evolving field from succumbing to the UV catastrophe. Overall this approach gives good prospects for c-field calculations that are quantitatively accurate without tweaking arbitrary technical parameters.

Thursday 22nd February

Invited
22 Feb
8.50am

2D Quantum Turbulence in atomic BECs: An Overview

Brian P Anderson
College of Optical Sciences, University of Arizona

The statistical mechanics of point vortices in a bounded two-dimensional (2D) domain was analyzed by Onsager in 1949 [1]. Although Onsager's discussion is widely recognized as the conceptual origin of quantized circulation of vortices in a superfluid, it primarily serves as a foundation for understanding the phenomenology of turbulence in 2D superfluids, the central issue of this talk. While point-vortex models of 2D turbulence have been examined in depth in mathematical and numerical contexts for decades, the field of 2D *quantum* turbulence (2DQT) has recently developed into an active area of theoretical and experimental research involving far-from-equilibrium fluid dynamics of atomic-gas BECs. Here, 2DQT loosely means disordered distributions of point-like vortices of quantized circulation within a superfluid, a definition that we will elaborate upon. In this talk, we will review some of the theoretical and experimental progress of the last few years related to vortex dynamics and 2DQT in BECs. In order to give a broad context to related talks at this conference and convey some of the excitement of this field of research, we will discuss why BECs are an interesting and useful platform for such studies, and mention some of the significant open problems and challenges of the field.

[1] L. Onsager, "Statistical Hydrodynamics." Il Nuovo Cimento v.6, suppl. to issue 2, 279 (1949).

Invited
22 Feb
9:30am

Impact of a Vortex Core

Tapio Simula
Monash University

The inertial mass of a vortex in a superfluid is a conundrum that has been debated in the literature for some time. The vortex mass may influence many phenomena including condensation of vortices in two-dimensional quantum turbulence, potential continuous gravitational wave emission from rotating neutron stars, vortex pinning in high-temperature superconductivity, and braiding of non-Abelian vortex anyons in a topological quantum computer.

We will derive an equation of motion for a vortex in a weakly interacting Bose-Einstein condensate and use it to express the inertial mass of a quantised vortex in terms of the vortex core localised kelvon quasiparticle analogous to the Kelvin wave excitation of a classical vortex. The inertial mass of a vortex in Bose and Fermi systems is found to have the same origin as the elementary vortex core localised quasiparticle states.

We will suggest how the inertial mass, the Magnus force, and the geometric Berry phase of a quantised vortex could be measured experimentally in cold Bose and Fermi gases and how the inertial mass of a quantised vortex in a Bose-Einstein condensate could be optically tuned.

Negative temperature vortex states of a 2D superfluid

Hot Topic
22 Feb
10:10am

Tyler W. Neely[1], Guillaume Gauthier[1], Matthew T. Reeves[1], Xiaoquan Yu[2], Ashton S. Bradley[2], Mark Baker[1], Thomas A. Bell[1], Halina Rubinsztein-Dunlop[1], Matt J. Davis[1]

[1]University of Queensland, ARC Centre of Excellence for Engineered Quantum Systems, [2]Dodd-Walls Centre, University of Otago

Bose-Einstein condensates (BECs) present a nearly ideal experimental test-bed for 2D vortex physics, due to their close correspondence to a point vortex system. BECs have thus been proposed as system for the observation of the high-energy states of vortex motion first predicted by Onsager. We report our observation of such negative-temperature vortex states injected directly into a uniform elliptical BEC [‘]. Stirring the condensate with a pair of elliptical barriers, we produce a vortex dipole consisting of 9 vortices on average per cluster and a clustered fraction approaching 100%. We find that over many seconds of hold time vortex annihilation is suppressed and the clustered fraction is stable. However, the system exhibits energy loss (cooling) with increasing hold time. We characterise the cooling rate in response to variable non-uniformity of the BEC density and finite temperature. We also perform momentum spectroscopy, showing that a kinetic energy signature of the vortex clusters gives an extra measure of energy loss. In addition to representing the first observations of fully clustered negative temperature vortex states, these results inform the experimental feasibility of observing Onsager vortex states arising dynamically from the evaporative heating mechanism.

[1] G. Gauthier, M. T. Reeves, X. Yu, A. S. Bradley, M. Baker, T. A. Bell, H. Rubinsztein-Dunlop, M. J. Davis, T. W. Neely, Negative-Temperature Onsager Vortex Clusters in a Quantum Fluid, https://arxiv.org/abs/1801.06951

Observation of negative absolute temperatures in superfluid vortices

Hot Topic
22 Feb
10:30am

Kristian Helmerson, Shaun Johnstone, Andrew Groszek, Tapio Simula

Monash University

We have observed negative absolute temperature configuration of vortices in a 2D superfluid atomic gas of Rb atoms confined in a circular-shaped, flat-bottom potential [1]. We create the vortex configurations by sweeping a linear array of optical barriers through the cloud of atoms and then allow the system to evolve for a variable time during which vortex-antivortex annihilation occurs. We subsequently use velocity-selective Bragg scattering and absorption imaging to identify the sign of the circulation and location of the vortices, which enables us to determine the incompressible flow field of the atomic gas. We perform thermometry on the vortex configurations by identifying the numbers of clusters, dipoles and free vortices. By varying the width and spacing between the optical barriers, we are able to create vortex configurations going from positive to negative absolute temperatures. We also observe some evaporative heating of the vortex configuration as vortices are lost due to annihilation.

[1] S. P. Johnstone, A. J. Groszek, P. T. Starkey, C. J. Billing, T. P. Simula, K. Helmerson, Negative absolute temperatures of vortices in a two-dimensional superfluid, https://arxiv.org/abs/1801.06952

Invited
22 Feb
11:30am

Decaying 2D Turbulence in an Atomic Superfluid

Yong-Il Shin
Seoul National University

Quantum turbulence (QT) has been studied for decades in superfluid helium, leading to an intriguing comparative study between QT and classical turbulence. In a two-dimensional (2D) classical fluid, a large-scale flow structure emerges out of turbulence, which is known as the inverse energy cascade. An interesting question is whether this phenomenon can occur in an inviscid and irrotational superfluid. In this talk, I will present our experimental study of decaying 2D QT with atomic Bose-Einstein condensates (BECs) of highly oblate geometry. We prepared a turbulent BEC by stirring it with a repulsive optical potential and investigated its relaxation for various temperatures. We observed nonexponential decay behavior of the vortex number, which is attributable to the vortex-antivortex pair annihilation process, and we found that the vortex decay rate is almost linearly proportional to mutual friction coefficient which was separately measured from long-time dynamics of a corotating vortex pair. By detecting the circulation directions of vortices as well as their positions, we could obtain full information on the vortex configuration of decaying turbulence. At our lowest temperature of about $0.5T_c$, where T_c is the superfluid critical temperature, we observed that weak spatial pairing between vortices and antivortices develops in the turbulent BEC. Finally, I will describe in brief our ongoing experiment for examining various 2D turbulence regimes in the BEC system.

Topological phases of mixed states

Invited
22 Feb
12:10pm

Michael Fleischhauer
Univ. of Kaiserslautern, Dept. of Physics & Reserach Center OPTIMAS

Topological states of matter have fascinated physicists since a long time due to the exotic properties of elementary excitations and the topological protection of edge states and currents. The notion of topology is ususally associated with ground states of (many-body)-Hamiltonians. So what is left of it at finite temperatures? Moreover, can topological protection be extended to systems with losses? Motivated by topological charge pumps, first introduced by Thouless, I will discuss a classification for topological phases of matter applicable to finite-temperature states as well as stationary states of driven, dissipative systems based on the many-body polarization. In contrast to charge transport, the polarization can be used to probe topological properties of non-interacting and interacting closed and open systems alike and remains a meaningful quantity at finite T. For non-interacting fermions it defines a topological invariant, the ensemble topological phase (ETP) [1]. I discuss the physical significance of the ETP and specific examples such as a Thouless pump in the steady state of one-dimensional lattices driven by Markovian reservoirs [2] and the finite-temperature Rice-Mele and Harper-Hofstadter models.

[1] C.E. Bardyn, L. Wawer, A. Altland, M. Fleischhauer, S.Diehl (Phys.Rev. X 2018, arxiv: 1706.02741)
[2] D. Linzner, L. Wawer, F. Grusdt, M. Fleischhauer, Phys. Rev. B 94, 201105 (2016)

Two Intriguing Examples for Topological Effects in Ultracold Atoms

Hot Topic
22 Feb
12:50pm

Axel Pelster
University of Kaiserslautern, Germany

We discuss two specific bosonic lattice systems where topological effects occur.

At first, we analyze the ground-state properties of anyons in a one-dimensional lattice using the Anyon-Hubbard Hamiltonian [1]. To this end we map the hopping dynamics of correlated anyons to an occupation dependent hopping Bose-Hubbard model using the fractional Jordan-Wigner transformation. In particular, we calculate the quasi-momentum distribution of anyons, which interpolates between Bose-Einstein and Fermi-Dirac statistics. Combining analytical and numerical methods it turns out that the anyonic quasi-momentum distribution reveals both a peak-shift and an asymmetry which mainly originates from the nonlocal string property.

Afterwards, we investigate the extended hard-core Bose-Hubbard model on the triangular lattice as a function of spatial anisotropy with respect to both hopping and nearest-neighbor interaction strength [2]. At half-filling the system can be tuned from decoupled one-dimensional chains to a two-dimensional solid phase with alternating density order by adjusting the anisotropic coupling. At intermediate anisotropy, however, frustration effects dominate and an incommensurate supersolid phase emerges, which is characterized by incommensurate density order as well as an anisotropic superfluid density. We demonstrate that this intermediate phase results from the proliferation of topological defects in the form of quantum bosonic domain walls. To this end we analyze how both the structure factor and the anisotropic superfluidity can be interpreted in terms of these topological defects.

[1] G. Tang, S. Eggert, and A. Pelster, New J. Phys. 17, 123016 (2015).
[2] X.-F. Zhang, S. Hu, A. Pelster, and S. Eggert, Phys. Rev. Lett. 117, 193210 (2016).

Invited
22 Feb
2:30pm

Renyi Entropies from Random Quenches in Atomic Hubbard and Spin Models

Peter Zoller

Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information, Austria Academy of Sciences, Innsbruck, Austria

We are interested in quench dynamics in atomic Hubbard and spin models with controlled disorder [1], as available in present atomic optical lattice experiments and with single site addressability. We study a sequence of such quenches generated by disordered lattice Hamiltonians, and we are interested in convergence of these operations to "random unitaries" (i.e. drawn from a Circular Unitary Ensemble (CUE)). This is a problem intimately connected to thermalization dynamics of periodically driven quantum many-body systems, and quantum chaos. Our aim is to implement "random measurements" in the quantum many-body system, where a random quench is followed by observation with a quantum gas microscope. Remarkably, such random measurements allow extraction of Renyi (entanglement) entropies for single copies of a quantum many-body system, which is of interest as a unique tool to characterize entanglement properties (including topology) of (non-)equilibrium quantum phases. We demonstrate feasibility of this protocol in present atomic experiments, including analysis of convergence of random quenches to CUE (2-design), and the required number of measurements. We discuss two examples: (i) measurement of an area law in 2D Heisenberg and Fermi Hubbard models, and (ii) measurement of entropy growth in a many-body localized phase.

[1] A. Elben, B. Vermersch, J. I. Cirac, and P. Zoller, in preparation.

Invited
22 Feb
3:10pm

Exploring adiabatic quantum dynamics of the Dicke model in a trapped ion quantum simulator

Ana Maria Rey

JILA, NIST and University of Colorado at Boulder

One of the most important goals of modern quantum sciences is to learn how to control and entangle many-body systems. In this talk I will report our recent effort to use a self-assembled 2D Coulomb crystal of ions in the presence of an external transverse field to engineer a quantum simulator of the Dicke Hamiltonian. The Dicke model features a quantum critical point separating two distinct phases: the superradiant (ferromagnetic) and normal (paramagnetic) phases. I will report on our effort to realize protocols that aim to adiabatically prepare the superradiant ground state, a spin-boson cat state with macroscopic phonon occupation, which is well-suited to enhanced metrology and quantum information processing. We measure the spin observables, both experimentally and in our simulations, to characterize the state of the system at the end of the ramp. We find that under current operating conditions an optimally designed ramp is not sufficient to achieve significant fidelity with the superradiant ground state. However, our theoretical investigation shows that slight modifications of experimental parameters, together with modest reductions in decoherence rates and thermal noise can increase the cat-state fidelity to 75% for 20 spins. These results open a path for the use of large ensembles of trapped ion crystals as powerful quantum sensors and quantum information processors.

Optically driven strongly correlated quantum systems

Invited
22 Feb
4:30pm

Dieter Jaksch
University of Oxford

Recent experimental progress indicates that selective and strong optical driving of phonons may generate or enhance ordered phases in strongly correlated quantum materials. This is achieved by driving the system far out of thermal equilibrium on a very short time scale where the dynamics is dominated by coherent quantum evolution. In my talk I will discuss a collection of approaches for gaining a better understanding of the fundamental physical processes that might underpin these experiments. I will focus on the study of driven toy models and mention novel approaches to the simulation of strongly correlated quantum systems as well as quantum-optics based experiments. The long-term aim of this work is to help developing optimized methods for optically controlling and steering dynamics far away from thermal equilibrium in quantum matter to induce new functionality. Specifically, I will consider a one-dimensional driven fermionic Hubbard model in the strongly correlated limit where the onsite interaction dominates over the kinetic energy. The driving is modelled as an alternating periodic modulation of the lattice site energy offsets. I will show how this modulation suppresses tunnelling and induces exchange interactions. The combination of these effects changes the nature of the system into an attractive Luttinger liquid and leads to enhanced fermion pairing in one spatial dimension. I will present results at zero and finite temperatures and discuss the prospect of observing driven out-of-equilibrium superconductivity in this model system. I will then move to novel hybrid quantum-classical approaches for DMFT simulations that promise to yield insights into the driven Hubbard model in higher spatial dimensions.

AC Josephson Effect in a Two-dimensional Superfluid: Algebraic Time-crystallization

Invited
22 Feb
5:10pm

Boris Svistunov
University of Massachusetts

The AC Josephson effect is a hallmark of superfluidity, indicative of the fundamental fact that along with breaking the global $U(1)$ symmetry, superfluids also break time-translation symmetry. For the superfluidity to take place, an algebraic (topological) order is sufficient. The conventional AC Josephson effect, however, is based on the notion of the global phase and thus requires genuine long-range order. We observe that the absence of the genuine long-range order in a finite-temperature two-dimensional superfluid manifests itself in an algebraic (to be contrasted to exponential, in the normal fluid) decay of the temporal current-current correlator for the Josephson current. The exponent controlling the algebraic decay is a universal function of the superfluid-stiffness-to-temperature ratio; this exponent can be also seen in the power-law singularity of the Fourier spectrum of the Josephson current.

Friday 23rd February

Invited
23 Feb
8:50am

Dynamics of impurities in quantum gases

Meera Parish
Monash University

The behaviour of a mobile impurity particle interacting with a quantum-mechanical medium is of fundamental importance in physics. Ultracold atomic gases have greatly improved our understanding of the impurity problem owing to the high degree of control over experimental parameters such as interactions and atom population. I will discuss recent theoretical and experimental progress in exploring the properties of impurities interacting with bosonic and fermonic mediums. In particular, I will introduce a new theoretical approach for describing the coherent non-perturbative quantum evolution following a quench of the impurity-medium interactions.

Hot Topic
23 Feb
9:30am

Low-lying excitations of a resonantly interacting Fermi gas across the superfluid transition

Sascha Hoinka
Swinburne University of Technology

We explore the temperature dependence of the elementary excitations below and above the superfluid phase transition in a near-homogeneous unitarity Fermi gas using low-momentum Bragg spectroscopy. In the long-wavelength regime, Bragg scattering probes collective excitations of the gas which are closely linked to the superfluid order parameter. The dominant feature in the measured Bragg spectra is a peak corresponding to the phonon mode, which shows dramatic changes in both amplitude and width across the superfluid to normal fluid transition. We can use this to study dynamic properties such as damping and the evolution of the sound speed. The latter allows also us to link the density response to the thermodynamics of the system via the pressure equation of state. We also present our progress towards the unresolved question of pseudogap pairing in a Fermi gas at unitarity.

Hot Topic
23 Feb
9:50am

Mesoscopic transport of cold fermions

Leonid Glazman
Yale University

We develop a theory of dissipative transport for a superfluid flowing through a quantum point contact. It allows us to determine the relaxation times for the particle number and temperature and to find the Seebeck coefficient of the point contact. The theory is inspired and provides some explanations for the results of experiments with cold, unitary gas of Li-6 atoms.

Excursions into phase space: the Otago ultracold atoms experiment

Hot Topic
23 Feb
10:10am

Niels Kjaergaard
Dodd-Walls Centre, University of Otago

We report on progress from the most remote BEC and DFG experiment in the world. Our work revolves around a steerable optical tweezer platform that can harness 3D configurations of multiple samples of ultracold atomic ensembles. In one application we deployed this system as a nano-eV optical collider [1] in which we for example studied the scattering of indistinguishable fermions [2] and explored Fano-Feshbach resonances in a parameter space spanned by both magnetic field and collision energy [3]. In particular, we will focus on a method to extract a narrow collisional resonance feature from its imprint on the particles? dynamical phase space.

[1] R. Thomas, M. Chilcott, C. Chisholm, A. Deb, M. Horvath, B. Sawyer & N. Kjærgaard, Quantum Scattering in an Optical Collider for Ultracold Atoms, J. Phys. Conf. Ser. 875, 012007 (2017).
[2] R. Thomas, K.O. Roberts, E. Tiesinga, A.C.J. Wade, P.B. Blakie, A.B Deb, & N. Kjærgaard, Multiple scattering dynamics of fermions at an isolated p-wave resonance, Nature Communications 7, 12069 (2016).
[3] M. Horvath, R. Thomas, E. Tiesinga, A. Deb & N. Kjærgaard, Above-threshold scattering about a Feshbach resonance for ultracold atoms in an optical collider, Nature Communications 8, 452 (2017).

Invited
23 Feb
11:10am

Cold Atom Sagnac Interferometry with Ring-Trapped Bose-Einstein Condensates

J L Helm[1], T P Billam[2], A Rakonjac[3], S L Cornish[3], S A Gardiner[3]

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

[2]Joint Quantum Center (JQC) Durham-Newcastle, School of Mathematics, Statistics and Physics, Newcastle University Newcastle upon Tyne NE1 7RU, United Kingdom.

[3]Joint Quantum Center (JQC) Durham—Newcastle, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom

Atomic Bose-Einsten condensates are often regarded as the coherent matter-wave equivalent relative to thermal atomic clouds of the laser relative to incoherent light. As such, when considering matter-wave interferometry, one might naturally expect atomic atomic Bose-Einstein condensates to provide a comparable boon as the invention of the laser does to optical interferometry, however the relatively strong effect of mean-field interactions complicates this simple picture. Nevertheless, our theoretical investigations have given us a number of options to consider, whereby astute design means the effects of interactions can be accommodated [1,2], or even advantageous [3].

There are two basic regimes: (1) repulsive interactions, where our approach has been to consider toroidal trapping configurations to substantially nullify forces arising from density gradients; and (2) attractive interactions where the approach is to consider some degree of quasi-one-dimensionality and bright soliton solutions. We also note that a key development in recent years is extraordinary technical progress in producing tailor made external potentials for cold atoms, using e.g. spatial light modulators, digital mirror arrays, etc.

[1] Spin-orbit coupled interferometry with ring-trapped Bose-Einstein condensates JL Helm, TP Billam, A Rakonjac, SL Cornish, SA Gardiner arXiv:1701.02154 (accepted for publication by Phys. Rev. Lett.)

[2] Sagnac Interferometry Using Bright Matter-Wave Solitons JL Helm, SL Cornish, SA Gardiner Phys Rev Lett 114 134101 (2015)

[3] Rotational response of two-component Bose-Einstein condensates in ring traps PL Halkyard, MPA Jones, SA Gardiner Phys Rev A 81 061602(R) (2010)

Binary Condensate Mixtures: Phase Separation, Expansion & Thermalisation

Invited
23 Feb
11:50am

Nick Proukakis
Joint Quantum Centre (JQC) Durham-Newcastle, Newcastle University

The miscibility of trapped atomic binary mixtures is typically examined after time-of-flight expansion using a homogeneous mean-field criterion based on the relation between inter- and intra-component interaction strengths.

Considering initially a trapped condensate mixture with overlapping trap centres, we show that the in situ miscible-immiscible transition depends critically on the condensate numbers, deviating from this simple homogeneous prediction; we demonstrate that this transition can be mapped out experimentally by measuring the damping rate and the frequency of the dipole oscillations [1].

We next consider the role of trap sag in the coupled expansion dynamics at different temperatures. By performing the first full numerical analysis of time-of-flight expansion dynamics for $T > 0$, we observe the emergence of striking density features, numerically reproducing observations in ^{87}Rb-^{39}K experiments. We also demonstrate that the homogeneous phase-separation criterion actually emerges dynamically in mixtures during expansion as a result of mechanical equilibrium across the condensate interface region, without however a clear transition point between the miscible and immiscible phases. Importantly, we find the presence of a non-negligible gravitational sag to be advantageous for identifying this transition region [2].

Our simulations are conducted at non-zero temperatures and are based on coupled condensate-Boltzmann cloud ("ZNG") description of the mixture [3], which also facilitate the study of thermalisation in such mixtures [4].

We acknowledge funding from EPSRC.

[1] Lee et al., PRA, 94, 013602 (2016).
[2] Lee et al., arXiv:1712.07481 (2017).
[3] Edmonds et al., PRA, 91, 011602(R) (2015).
[4] Lee et al., JPB, 49, 214003 (2016).

Poster Abstracts

Poster Session Thursday 22nd February

Thermalisation of an out of equilibrium Bose Gas

1

Maarten Hoogerland
University of Auckland

We experimentally study the thermalization of a Rubidium 87 Bose-Einstein condensate far from equilibrium in a harmonic trap. We measure the rate of thermalization along with the rate of condensate growth and compare the results to finite temperature theory. We observe the spontaneous formation of defects resulting from the inhomogeneous Kibble-Zurek mechanism, which we identify as grey solitons.

Study of decay of superflow of a Bose-Einstein condensate in a ring trap

2

Masaya Kunimi
Yukawa Institute for Theoretical Physics, Kyoto University

Recently, the NIST group has experimentally observed temperature-dependent decay of superflow of a Bose-Einstein condensate in a ring trap [1]. They found that the decay rate (inverse of the lifetime) is inconsistent with the Arrhenius law, which should be obeyed if the decay is due to thermally activated phase slips (TAPS). However, their estimation of the energy barrier, which determines a dominant contribution to the temperature dependence of the lifetime, is not quantitatively accurate so that more profound theoretical analyses are needed in order to examine the possibility of the superflow decay via TAPS. In this work, we calculate the lifetime of the superflow due to the thermally activated phase slips by using the Kramers formula with the mean-field theory [2,3]. Our theoretical results show that the lifetime is much lager than the experimental lifetime. This means that the thermally activated phase slips can not explain the experimental results. Alternatively, we find that three-body loss can induce the decay of superflow. We also propose the short-time experiment to confirm whether or not the three-body loss affects the decay of superflow.

[1] A. Kumar, et al., Phys. Rev. A 95, 021602(R) (2017).
[2] J. S. Langer, Ann. Phys. 54, 258 (1969).
[3] M. Kunimi and I. Danshita, Phys. Rev. A 95, 033637

3

Finite-temperature Effects on Producing Smooth Flow in a Racetrack Atom Circuit

Mark Edwards[1], Benjamin Eller[1], Olatunde Oladehin[1], Charles Clark[2]

[1]Physics, Georgia Southern Univ., [2]Joint Quantum Institute, University of Maryland

We studied smooth flow produced by stirring an ultracold atom circuit consisting of a gaseous Bose–Einstein condensate (BEC) confined in a "racetrack" potential at finite temperature. The BEC is assumed to be strongly confined in a horizontal plane by a vertical harmonic trap and, within this plane, subjected to an arbitrary two–dimensional potential. The racetrack potential is made up of two straight parallel channels connected on both ends by semicircular channels of the same width and (energy) depth as the straightaways. We used the Zaremba–Nikuni–Griffin model to simulate the behavior of the BEC and noncondensate in this potential when stirred by a rectangular paddle at various speeds and barrier heights. We compare the amount of flow produced by stirring under these conditions with the flow produced under the same conditions but at zero temperature. We discuss how a simple model which predicts the flow produced by stirring at zero temperature could be modified for finite temperature.

4

Superfluid transport dynamics through a resistive channel

Guillaume Gauthier

The University of Queensland

In 1955, Feynman predicted that a superfluid flowing through a small channel into a large superfluid reservoir would experience a contact conductance that scales as the square of the size of the constriction, w^2, due to seeding of vortices needed to make up for the induced vorticity of the flow [1]. To date, direct testing and confirmation of this scaling law have remained elusive. Utilising our highly configurable optical potentials for BECs [2], we produce a dumbbell geometry that connects two reservoirs with a tunable channel. I will present our experimental results for the resistance scaling in these mesoscopic channels. We additionally determine the applicability of lumped circuit models for describing the transport dynamics of the dumbbell system.

[1] R. P. Feynman, in Prog. Low Temp. Phys., edited C. J. Gorter (North-Holland Publishing Company, Amsterdam, 1955) Chap. 2, p. 17.
[2] G. Gauthier et al, Optica, 3 (10), 1136-1143, 2017.

5

Dynamics of a Bose-Einstein condensate in a time-averaged ring trap

Thomas A Bell
The University of Queensland

Rapidly scanning magnetic and optical dipole traps have been used in many laboratories to form time-averaged potentials for ultracold quantum gas experiments. Here we theoretically and experimentally characterise the dynamical properties of Bose-Einstein condensates in ring-shaped potentials that are formed by scanning a optical dipole beam along a circular trajectory. We find that this procedure leads to a non-trivial phase profile on the condensate that can be approximated analytically using the concept of phase imprinting. While the phase profile is not apparent in in- trap imaging, time-of-flight expansion leads to clear signatures in the density of of an in-trap phase step in the condensate that is coincident with the instantaneous position of the scanning beam. The phase step is measurable even when scanning the beam at frequencies two orders of magnitude larger than the characteristic frequency of the trap. We map out the properties of the condensate in the scanning trap both experimentally and using numerical simulations and find excellent agreement. Furthermore, we demonstrate that bidirectional scanning of the ring mostly eliminates the phase gradient about the ring away from the beam location, and renders the system more suitable for coherent matter wave interferometry.

6

Negative-mass effects in exciton-polaritons and spin-orbit coupled Bose-Einstein condensates

David Colas

School of Mathematics and Physics, The University of Queensland, Australia

Negative effective masses can be achieved by engineering the dispersion relation in a range of quantum systems. Examples include holes within semiconductors, exciton-polaritons in 2D microcavities, or spin-orbit coupled Bose-Einstein condensates (SOCBEC). A recent experiment with SOCBEC has shown that a negative effective mass parameter can halt the expansion of a BEC, and resulted in density fringes in the condensate [1]. We show that the observed fringes are due to the self-interference of the wave packet, and occur due to the underlying and universal linear effect of non-parabolic dispersion. This effect has previously been predicted in polariton systems [2] on a time scale that is more than nine orders of magnitude faster . Here we contrast these two platforms, and clarify the influence of interactions.

We also show the experimental observations of Ref. [1] rely on only one of the two effective mass parameters that characterize the dispersion relation. We demonstrate configurations accessible in SOCBECs (but not exciton-polaritons) when both mass parameters controlling the propagation and diffusion of the condensate are negative, resulting in the novel phenomenon of counter-propagating self-interfering packets.

[1] Khamehchi et al., Phys. Rev. Lett. 118, 155301 (2017).
[2] D. Colas and F.P. Laussy, Phys. Rev. Lett. 116, 026401 (2016).
[3] D. Colas, F.P. Laussy and M. J. Davis, in preparation.

7

Signatures of Anderson Localisation in the presence of spin–orbit coupling

John Helm

Dodd-Walls Centre, University of Otago

In order to better study Anderson Localisation (AL), we seek easily measurable observables which characterise the metal-insulator phase transition. Recent experimental observations of the coherent forward/back scattering peaks (CFS/CBS) in the momentum space of the wave function have confirmed these features as viable candidates for such a observables. However, the CFS and CBS have not yet been fully characterised in all possible symmetry classes. Here we describe the background of these features and outline how they appear in spin-orbit coupled systems, where the symplectic symmetry is broken.

Quantum and thermal fluctuations in a Raman spin-orbit-coupled Bose gas

8

Xiaolong Chen
Swinburne University of Technology

We theoretically study a three-dimensional weakly interacting Bose gas with Raman-induced spin-orbit coupling at finite temperature. By employing a generalized Hartree-Fock-Bogoliubov theory with Popov approximation, we determine a complete finite-temperature phase diagram of three exotic condensation phases (i.e., the stripe, plane-wave, and zero-momentum phases), against both quantum and thermal fluctuations. We find that the plane-wave phase is significantly broadened by thermal fluctuations. The phonon mode and sound velocity at the transition from the plane-wave phase to the zero-momentum phase are thoughtfully analyzed. At zero temperature, we find that quantum fluctuations open an unexpected gap in sound velocity at the phase transition, in stark contrast to the previous theoretical prediction of a vanishing sound velocity. At finite temperature, thermal fluctuations continue to significantly enlarge the gap, and simultaneously shift the critical minimum. For a Bose gas of ^{87}Rb atoms at the typical experimental temperature, $T = 0.3T_0$, where T_0 is the critical temperature of an ideal Bose gas without spin-orbit coupling, our results of gap opening and critical minimum shifting in the sound velocity are qualitatively consistent with the recent experimental observation

[1] Ji et al., Phys. Rev. Lett. 114, 105301 (2015).

Isolated coarsening dynamics in a one-dimensional ferromagnetic spinor Bose gas

9

Kazuya Fujimoto
University of Tokyo

Coarsening is a ubiquitous relaxation dynamics caused by a quench of system's parameters or external fields across a phase transition point. Originally, it has been intensively investigated in various classical systems with dissipation such as a metal alloy and a binary liquid, and their dynamics is known to be classified into several universality classes [1]. Against this backdrop, we address the following question: "Does there exist any coarsening universality class unique to isolated systems?". To answer this, we analytically and numerically study a one-dimensional (1D) coarsening dynamics in a ferromagnetic spin-1 Bose-Hubbard model, finding an unconventional universality class unique to isolated 1D systems [2]. In this presentation, we show the analytical and numerical results based on the singular perturbation method and the truncated Wigner approximation.

[1] A. J. Bray, Adv. Phys. 43, 357 (1994).
[2] K. Fujimoto, R. Hamazaki, and M. Ueda, arXiv:1707.03615.

10

Thermalisation of a quenched spinor condensate

Lewis Williamson
Dodd-Walls Centre, University of Otago

The long time non equilibrium dynamics of isolated systems quenched across a phase transition has been an active area of research in recent years. Such a quench breaks symmetry locally, leading to small domains of distinct order parameter orientation. The approach to an ordered phase involves the growth of these domains, which is often associated with the annihilation of topological defects. For large domain size, the dynamics can become scale invariant. This process is known as 'coarsening dynamics'. Alternatively, non equilibrium dynamics can be explored from the perspective of turbulence, driven either by vortex or wave interactions, leading to cascades of energy and particles in spectral space. The role of turbulence and its relation to coarsening dynamics remains largely unexplored.

The universal coarsening dynamics of a spin-1 condensate quenched to an easy-plane ferromagnetic phase was explored in recent work [1], where it was found that the scale invariant growth of domains is driven by the annihilation of vortices. In the present work we show that long after all vortices have annihilated this system still has not thermalised. Instead, the system establishes an extremely long-lived energy cascade driven by wave interactions (wave turbulence). The transport of energy from out-of-equilibrium long wavelength modes to a short wavelength thermal field is associated with a second slowly growing length scale. This work connects wave turbulence with the theory of coarsening dynamics, and establishes a much more complete picture of the thermalisation of the quenched spin-1 system.

[1] Lewis A. Williamson and P. B. Blakie, Physical Review Letters 116, 025301 (2016).

Spinor turbulence in antiferromagnetic spin-1 Bose-Einstein condensates

11

S. Kang, J. H. Kim, S. W. Seo, Y. Shin
Seoul National University

We present turbulence experiments with quasi-two-dimensional antiferromagnetic spin-1 Bose-Einstein condensates. We investigate the phase-transition dynamics from the easy-axis polar phase to the easy-plane polar phase, which is initiated by suddenly changing the sign of the quadratic Zeeman energy q. We observe the emergence and decay of spin turbulence and the formation of half-quantum vortices (HQVs) in the quenched condensate. The characteristic time and length scales of the turbulence generation dynamics are proportional to $|q|^{-1/2}$ as inherited from the dynamic instability of the initial state. In the evolution of the spin turbulence, spin-wave excitations develop from large to small length scales, suggesting a direct energy cascade, and the spin population for the axial polar domains exhibit a nonexponential decay. We also investigate the critical spin superflow dynamics in the easy-plane polar phase. Above a certain critical flow rate, dark-bright solitons are generated due to the modulation instability of the counterflow of two spin components and spin turbulence emerges as the solitons decay because of their snake instability. We identify another critical point for spin superflow, in which transverse magnon excitations are dynamically generated via spin-exchanging collisions, which leads to transient formation of axial polar spin domains and their subsequent quench into spin turbulence.

Simulating an experimental quench for an anti-ferromagnetic spin-1 condensate

12

Luke Symes
University of Otago

We investigate recent experimental results for an anti-ferromagnetic spin-1 condensate quenched between easy-axis and easy-plane nematic phases [1]. The quench is carried out by changing a quadratic Zeeman interaction parameter from positive to negative, resulting in a discontinuous phase transition.

The post-quench ground state — the easy-plane nematic phase — spontaneously breaks a continuous spin symmetry. We have developed theory for studying the long-time dynamics of this phase transition in the homogenous case [2]. The system is characterized by antiferromagnetic order in each nematic phase, but during the quench develops transitory ferromagnetic order as the initial ground state order breaks up and evolves towards the new ground state. The experimental group measured the decay of the initial order and the dynamics of magnetic fluctuations.

We verify their results with simulations using the same experimental parameters, including a harmonic trapping potential. We find interesting spatial features in the early-time dynamics which did not appear in the homogeneous system, in agreement with experiment. We get good qualitative agreement for the decay of the initial population and magnetization fluctuations, with a slight difference in time scale and magnitude. We also measure the new order parameter of the easy-plane phase, and show that this saturates at long times.

[1] S. Kang, S. W. Seo, J. H. Kim, Y. Shin, Emergence and scaling of spin turbulence in quenched antiferromagnetic spinor Bose-Einstein condensates, Phys. Rev. A (2017) 053638
[2] L. M. Symes, P. B. Blakie, Nematic ordering dynamics of an antiferromagnetic spin-1 condensate, Phys. Rev. A (2017) 013602 .

13

Two-dimensional Condensation of Polar Molecules in a Synthetic Gauge Field

I-Kang Liu, Shih-Chuang Gou and Daw-Wei Wang

Department of Physics and Graduate Institute of Photonics, National Changhua University of Education, Changhua, Taiwan, and Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

In this presentation, we theoretically study the behaviour of a two-dimensional ultra-cold polar molecule gas in the condensate phase and subjected to an effective vector potential induced by the Raman coupling between two rotational levels of the molecule [1]. We consider the situation when the dipole moment connecting the two rotational levels is aligned by a DC field in the direction perpendicular to that of the two counter-propagating Raman beams. Based on the previous studies [2,3] , such setup can facilitate to engineer an effective long-range interaction featuring not only the standard dipolar form but also a spatial dependence on the relative phase between the two rotational states. Under the mean-field approximation, we study the ground state properties of the Bose-Einstein condensate consisting of such polar molecules and find that in the interaction dominant regime, the system energetically favours a Stoner-type ferromagnetic state when there is a 90 degree phase difference between the two rotational states. For the different regimes of Raman coupling and interaction strengths, we numerically solve Gross-Pitaevskii equation to investigate the groundstates of the system.

[1] Phys. Rev. A 92, 013604 (2015).
[2] Phys. Rev. A 78, 043604 (2007).
[3] Phys. Rev. A 81, 031601 (2010).

14

From two to many: dipolar bosons in a trap

Rafał Ołdziejewski

Center for Theoretical Physics PAS, Warsaw, Poland

I will present exact solutions for two dipolar particles in a 3D trap. I will compare magnetic and electric dipoles. External field free analog to the celebrated Einstein-de Haas effect will be discussed. Then I will consider a few polarized dipoles in a quasi 1D ring trap. Rotons, dark solitons and quantum droplets will be discussed.

15

Dipolar Droplets

Danny Baillie

University of Otago

Experiments with Bose-Einstein condensates of dysprosium and erbium atoms have observed the formation of dilute quantum gas droplets that can preserve their form, even in the absence of any external confinement. These droplets are stabilized by Lee-Huang-Yang quantum fluctuation corrections to meanfield theory. We discuss the regimes in which such self-bound droplet states are stable, and examine the properties of their collective excitations. Notably we observe that the elongated filament-shaped droplets act as a quasi-one-dimensional waveguide along which low angular momentum phonons propagate.

Dipolar Bose-Einstein Condensates with Weak Disorder

16

Axel Pelster
Department of Physics and Research Center Optimas, University of Kaiserslautern, Germany

We report on recent progress in understanding the properties of ultracold bosonic atoms in potentials with quenched disorder. This notoriously difficult dirty boson problem is experimentally relevant for the miniaturization of BECs on chips and can also be studied by tailoring disorder potentials via laser speckle fields. Theoretically it is intriguing because of the competition of localization and interaction as well as of disorder and superfluidity.

At first, we work out both a perturbative and a non-perturbative approach for dealing with dirty bosons with contact interaction for the homogeneous as well as for the harmonically trapped case [1-7]. In particular, we discuss under which conditions a Bose-glass phase emerges, which is characterized by mini-condensates in the local minima of the random potential. Afterwards, we consider the impact of weak disorder upon a homogeneous polarized dipolar Bose-Einstein condensate at both zero and finite temperature [8-10]. We find that disorder corrections of the superfluid density yield characteristic dipolar interaction-induced anisotropies, which affect both first and second sound.

[1] M. Timmer, A. Pelster, and R. Graham, Europhys. Lett. 76, 760 (2006)
[2] G.M. Falco, A. Pelster, and R. Graham, Phys. Rev. A 75, 063619 (2007)
[3] G.M. Falco, A. Pelster, and R. Graham, Phys. Rev. A 76, 013624 (2007)
[4] R. Graham and A. Pelster, J. Bifur. Chaos 19, 2745 (2009)
[5] T. Khellil and A. Pelster, J. Stat. Mech. 063301 (2016)
[6] T. Khellil, A. Balaž, and A. Pelster, New J. Phys. 18, 063003 (2016)
[7] T. Khellil and A. Pelster, J. Stat. Mech. 093108 (2017)
[8] C. Krumnow and A. Pelster, Phys. Rev. A 84, 021608(R) (2011)
[9] B. Nikolić, A. Balaž, and A. Pelster, Phys. Rev. A 88, 013624 (2013)
[10] M. Ghabour and A. Pelster, Phys. Rev. A 90, 063636 (2014)

Emergent Non-Eulerian Hydrodynamics of Quantum Vortices in Two Dimensions

17

Xiaoquan Yu, Ashton Bradley
Dodd-Walls Centre, University of Otago

We develop a coarse-grained description of the point-vortex model, finding that a large number of planar vortices and antivortices behave as an inviscid non-Eulerian fluid at large scales [1]. The emergent binary vortex fluid is subject to anomalous stresses absent from Euler's equation, caused by the singular nature of quantum vortices. The binary vortex fluid is compressible, and has an asymmetric Cauchy stress tensor allowing orbital angular momentum exchange with the vorticity and vortex density. An analytic solution for vortex shear flow driven by anomalous stresses is in excellent agreement with numerical simulations of the point-vortex model.

[1] X. Yu, A. S. Bradley, Physical Review Letters 119, 185301 (2017).

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Snell's Law for a quantum vortex dipole in a Bose-Einstein condensate

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We present recent work on the propagation of a quantum vortex dipole in a uniform Bose-Einstein condensate containing a step-change in the background superfluid density. The component of dipole momentum parallel to the interface is conserved, imposing a Snell's law relation between incident and refracted angle of the dipole.

The absolute maximum speed of a dipole is set by the separation scale where the vortices form a Jones-Roberts soliton, losing their strict topological nature. Quantum vortex dipoles are composed of vortex anti-vortex pairs, which cease to have well defined individual core structures below a minimum separation distance where they form a Jones-Roberts soliton.

Accounting for the energy shift associated with the vortex core change when crossing the interface, and the upper limit to the dipole velocity, we define an index of refraction for quantum vortex dipoles in a superfluid. The predictions of the resulting Snell's law relation are confirmed by systematic numerical simulations of the Gross-Piteavskii equation for a wide range of incident angles. Near the critical angle for total internal reflection, the strict optical analogy breaks down due to the finite dipole scale.

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Enstrophy Cascade in Decaying Two-Dimensional Quantum Turbulence

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University of Queensland

We report evidence for an enstrophy cascade in large-scale point-vortex simulations of decaying two-dimensional quantum turbulence [1]. Devising a method to generate quantum vortex configurations with kinetic energy narrowly localized near a single length scale, the dynamics are found to be well characterized by a superfluid Reynolds number Re_s that depends only on the number of vortices and the initial kinetic energy scale. Under free evolution the vortices exhibit features of a classical enstrophy cascade, including a k^{-3} power-law kinetic energy spectrum, and constant enstrophy flux associated with inertial transport to small scales. Clear signatures of the cascade emerge for $N > 500$ vortices. Simulating up to very large Reynolds numbers ($N = 32768$ vortices), additional features of the classical theory are observed: the Kraichnan-Batchelor constant is found to converge to $C' \approx 1.6$, and the width of the k^{-3} range scales as $\mathrm{Re}_s^{1/2}$

[1] M. T. Reeves, T. P. Billam, X. Yu, A. S. Bradley, Phys. Rev. Lett. 119, 184502 (2017)

Negative absolute temperatures of vortices in a two-dimensional superfluid

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Turbulent fluid flow is often characterised by the presence of vortices and swirls across many length scales. In 2D turbulence the swirling motion injected into the fluid can evolve towards persistent large-scale structures, such as the Great Red Spot and banded jets of Jupiter. An explanation for such behaviour was offered by Lars Onsager, who considered a model of 2D fluid flow based on quantised point-like vortices, showing that higher energy fluid flow statistically favours clustering of same-sign vortices, which he ascribed to negative absolute temperature vortex distributions. Onsager's model qualitatively explains the commonly observed feature of large-scale vortex structures in nearly two-dimensional fluid flow; however, the realisation of negative absolute temperature states in the statistical distribution of quantised vortices has remained elusive. Here we report the first observation of negative absolute temperature states of 2D quantised vortices in a superfluid gas of atoms. By dragging a grid barrier through an oblate superfluid Bose-Einstein condensate (BEC) of rubidium-87 atoms we produce distributions of vortices constrained to move in two dimensions. We detect the circulation sign of the quantised vortices, which, together with a vortex classification algorithm, facilitates the observation of Onsager's negative temperature states. We create vortex distributions with a range of energies, enabling the observation of a cross-over from positive to negative absolute temperatures. Furthermore, we observe a vortex evaporative heating mechanism. Our results open a pathway for quantitative studies of negative absolute temperature physics of two-dimensional quantum turbulence and the condensation of Onsager vortices – a counterpart for the BKT transition.

Vortex thermometry for turbulent two-dimensional fluids

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Andrew Groszek

Monash University

We introduce a new method of statistical analysis to characterise the dynamics of turbulent fluids in two dimensions. We establish that in equilibrium the vortex distributions can be uniquely connected to the temperature of the vortex gas, and apply this vortex thermometry to characterise simulations of decaying superfluid turbulence [1]. We confirm the hypothesis of vortex evaporative heating leading to Onsager vortices proposed in Ref. [2], and find previously unidentified vortex power-law distributions in the dynamics.

[1] Groszek, A. J., Davis, M. J., Paganin, D. M., Helmerson, K., and Simula, T. P., arXiv:1702.05229 (accepted PRL).
[2] Simula, T., Davis, M. J., and Helmerson, K., Phys. Rev. Lett. 113, 165302 (2014).

22

Splitting instability of a doubly quantized vortex in uniform Bose-Einstein condensates at zero temperature

Hiromitsu Takeuchi
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We revisit the fundamental problem of the splitting instability of a doubly quantized vortex in uniform single-component superfluids at zero temperature. We analyze the system-size dependence of the excitation frequency of a doubly quantized vortex through large-scale simulations of the Bogoliubov–de Gennes equation. We found that the system remains dynamically unstable even in an infinite-system-size limit. Perturbation and semi-classical theories reveal that the splitting instability radiates a damped oscillatory phonon as a counterpart of a quasi-normal mode.

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Collision dynamics of two-dimensional non-Abelian vortices

Thomas Mawson
Monash University

The possible collision dynamics of a pair of quantised vortices are constrained by their dimensionality and the algebra of their characteristic topological invariants. In our numerical experiments, we studied the collision dynamics of vortex pairs with both Abelian and non-Abelian algebra, in a two-dimensional spin-2 Bose-Einstein condensate. Vortex pairs with Abelian algebra were confirmed to either annihilate or pass through each other. Non-Abelian vortex pairs were identified to undergo a new collision event, coined rungihilation, in which the colliding vortices fuse into a rung vortex. In subsequent dynamics, the rung vortex is observed to decay into another pair of non-Abelian vortices with different topological charges to the initial pair. The novel topological effects of rungihilation are anticipated to produce a type of two-dimensional non-Abelian quantum turbulence, the characteristics of which are presently unknown.

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Experimental characterization of ultra-cold three body interactions

Luke Reynolds
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The view of few body dynamics in ultracold atom experiments is often blurred by an inevitably changing density profile. In order to avoid the consequential reliance on accurate modeling of the time dependent density profile, we develop a system capable of directly studying few body dynamics on the single event level. We use far off resonance optical tweezers to near-deterministically prepare three ^{85}Rb atoms in separate microtraps with 51% loading efficiency for all three atoms simultaneously. Each atom is then prepared in a specific hyperfine and magnetic sub-state and imaged by collecting fluorescence in an EMCCD camera to determine trap occupation. Currently, the system is being optimized to allow adiabatic merging of the three traps through the use of an acousto-optical modulator to observe and measure the rate coefficient for three body recombination, K_3.

Characterizing Feshbach resonances far above threshold

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Ryan Thomas
University of Otago

Feshbach resonances were originally described for scattering systems with fixed internal structures where the resonance would manifest as a peak in the elastic scattering cross section as a function of collision energy. In contrast, ultracold atomic physics is concerned with Feshbach resonances where the collision energy is fixed but the internal structure itself can be changed by, for instance, a magnetic field. It is this ability to change the interaction strength at vanishing energies that has made Feshbach resonances so versatile in the study of ultracold atomic gases. Here we marry the old approach to Feshbach resonances with the new, by using an all-optical atom-collider to study these resonances as a function of both energy and magnetic field in the collisions of potassium-40 and rubidium-87 atoms. By measuring the number of scattered atoms as a function of magnetic field for different energies, we map out the trajectory of the resonance through two-dimensional energy-magnetic field space and observe, for the first time, the interplay between a potential resonance in the open channel and the Feshbach resonance occurring due to the closed channel. We quantitatively compare our result with theoretical predictions from a coupled-channels model, and we find that retardation effects are necessary to accurately describe the position of our Feshbach resonances.

Towards measuring three-body correlations in unitary Fermi gases

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In quantum many body systems with short range interactions, numerous macroscopic and collective properties are inherited directly from the microscopic short range correlations between the particles. For example, in the case of a two-component Fermi gas with contact interactions of large scattering length, it was shown by N. Tan that one can link its thermodynamical behavior directly to the two-body correlator at close distance via a series of universal relations. Initially conceived in the context of cold atoms, this concept of the *contact* has, since then, been applied to various other systems, including neutron-proton interactions and even in coulomb gases, to give but a few examples. In quantum gases, inelastic losses due to strong interactions appear usually as unwanted effects that can hinder the observation of certain physical signatures of interest, a prominent example being the unitary bose gas which typically suffers from rather short lifetimes. However, such losses can also be turned into an advantage. For instance, by studying three-body losses of a bosonic impurity immersed in a Fermi superfluid and by making use of the aforementioned contact relations, our group recently showed that it is possible to directly probe the underlying two-body short range correlations. Here, we report on our progress on studying three-body short range correlations in a unitary Fermi gas, which, so far, have only been studied for bosons. To this end, we analyze three-body losses occurring in the vicinity of an s-wave Feshbach Resonance of a two-component Fermi gas of ^{40}K. This way, by employing a novel set of contact relations, one can gain insight into the thermodynamic properties of a strongly correlated Fermi gas with three-body interactions.

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Dissipative preparation of spin-entangled states of fermions in optical lattices

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The robust generation of highly entangled states have been one of the mayor focus in the field of quantum many-body systems due to its range of applications from metrology to quantum simulation. Dissipative dynamics provide a novel toolbox for the preparation of spin-symmetric states based on the fermionic statistics of atoms in an optical lattices and the coupling to a reservoir gas [1]. We incorporate ideas of previous proposals [2] based on two-body s-wave collisions to filter the spatial symmetries of our system through losses. By combining a Raman transfer between lattice bands and the dissipative coupling with a BEC reservoir, we dynamically filter out the desired spin symmetry sector preserving the particle number and generating a robust initial state for interferometry measurements.

[1] Phys. Rev. A 69, 022306 (2004).
[2] Phys. Rev. Lett. 109, 230501 (2012).

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Cooling schemes for two-component fermions in bilayer optical lattices

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In this presentation, I will discuss our recently proposed cooling scheme for two-component fermions in bilayer optical lattices. In particular, we modify a cooling scheme of Kantian et al. [1] utilizing bilayer structure to be effective for two-component fermions with much shorter sweep time. According to numerical simulations, our modified scheme can decrease the temperature of a system down to roughly half of its initial temperature with experimentally practical sweep time.

[1] A. Kantian et al., arXiv:1609.03579

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Localization in a Parity-time-symmetric Aubry-Andre model

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When the loss and gain in an open quantum system are balanced and obeys parity-time-symmetry (PT-symmetry), the eigenenergies spectrum can be entirely real despite that the Hamiltonian is non-Hermitian. However, if the gain-loss strength exceeds the intrinsic energy-scale of the system, the PT-symmetry can be spontaneously broken, where the spectrum can be partially or entirely complex. On the other hand, disorder potential can lead to localization of the quantum states, which in some cases will lead to an exponentially small PT-symmetry threshold. We study the effect of localization in a PT-symmetric Aubry-Andre model and investigate the interplay between disorder and loss-gain strength.

Exact analytical model for 1D BEC under bichromatic optical lattices under two- and three-body interactions

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Indian Institute of Information Technology Vadodara

We construct the family of explicit exact analytical solutions of one-dimensional cubic-quintic nonlinear Schrodinger equation (CQNLSE) for cigar shaped Bose Einstein condensate in the presence of space-modulated bi-chromatic optical lattice (BOL) and gain/loss. From our novel analytical model, we reveal the non-trivial form of system parameters: wavefunction, cubic and quintic nonlinearity, gain or loss etc. and their interrelation with each other. For illustration, we consider the case of cubic attractive and quintic repulsive nonlinearities and study the system dynamics. Interestingly, we identify the strength of cubic and quintic nonlinearity as the tuning parameter for controlling the localization of atomic population at the central lattice site of BOL. This result is confirmed by analysing the variation of energy per particle and condensate occupation number with respect to the strength of cubic and quintic interaction. Further, the periodic collapse and revival of condensate density are also demonstrated.

Exact nonequilibrium dynamics of finite-temperature Tonks-Girardeau gases

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We develop a new exact approach to compute the out-of-equilibrium dynamics of a finite-temperature Tonks-Girardeau gas. Using the Fredholm determinant approach and the Bose-Fermi mapping we show how the problem can be reduced to a single-particle basis, wherein the finite-temperature effects enter the solution via an effective “dressing” of the single-particle wavefunctions by the Fermi-Dirac occupation factors. The utility and computational efficiency of the approach is shown in two non trivial out-of-equilibrium scenarios: (i) collective breathing-mode oscillations in a harmonic trap, where we predict a striking collective manifestation of impenetrability—a collective many-body bounce effect, and (ii) collisional dynamics in the harmonically trapped Newton’s cradle setting involving the initial evolution in a periodic Bragg potential.

Non-equilibrium transport in two tunnel-coupled 1D quasicondensates

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Using finite-temperature c-field techniques, we study the non-equilibrium dynamics of two tunnel-coupled one-dimensional quasicondensates with temperature and chemical potential gradients. In particular, we characterise particle and energy transport where the two quasicondensates have initially the same temperature but different chemical potentials, the same chemical potential but different temperatures, and different chemical potentials and temperatures. We determine how these differences affect the transport scenarios between the two quasicondensates after a quench of the tunnelling strength.

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Universality of an impurity in a Bose-Einstein condensate

Jesper Levinsen
Monash University

We consider the ground-state properties of an impurity particle ("polaron") resonantly interacting with a Bose-Einstein condensate (BEC). Focusing on the equal-mass system, we use a variational wave function for the polaron that goes beyond previous work and includes up to three Bogoliubov excitations of the BEC, thus allowing us to capture both Efimov trimers and associated tetramers. We find that the length scale associated with Efimov trimers (i.e., the three-body parameter) can strongly affect the polaron's behaviour, even at densities where there are no well-defined Efimov states. However, by comparing our results with recent quantum Monte Carlo calculations, we argue that the polaron energy is a universal function of the Efimov three-body parameter for sufficiently low boson densities. We further support this conclusion by showing that the energies of the deepest bound Efimov trimers and tetramers at unitarity are universally related to one another, regardless of the microscopic model. On the other hand, we find that the quasiparticle residue and effective mass sensitively depend on the coherence length of the BEC, with the residue tending to zero as the coherence length diverges, in a manner akin to the orthogonality catastrophe.

[1] Shuhei M. Yoshida, Shimpei Endo, Jesper Levinsen, and Meera M. Parish, arXiv:1710.02968. To appear in PRX

34

Quantum Dynamics of Impurities Coupled to a Ultra-Cold Fermion Cloud

Weizhe Liu
Monash University

We computationally study the Ramsey-interferometry response of an impurity atom immersed in a fermion cloud at finite temperature by the Truncated Basis Method. Our theoretical result agrees with the one obtained from the functional determinant approach, and we will examine our results to recent experiments on dilute ^{40}K atoms in a ^{6}Li ultra-cold Fermion cloud.

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Brownian motion of a matter-wave bright soliton moving through a thermal cloud of distinct atoms

Rob McDonald, Ashton Bradley
Dodd-Walls Center, University of Otago

Taking an open quantum system approach, we derive a collective equation of motion for the dynamics of a matter-wave bright soliton moving through a thermal cloud of a distinct atomic species. The reservoir interaction involves energy transfer without particle transfer between the soliton and thermal cloud, thus damping the soliton motion without altering its stability against collapse. We derive a Langevin equation for the soliton center-of-mass velocity in the form of an Ornstein-Uhlenbeck process with analytical drift and diffusion coefficients. This collective motion is confirmed by simulations of the full stochastic projected Gross-Pitaevskii equation for the matter-wave field. The system offers a pathway for experimentally observing the elusive energy-damping reservoir interaction and a clear realization of collective Brownian motion for a mesoscopic superfluid droplet.

Quantum dark solitons in 1D quantum gases

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Joachim Brand
Massey University

We develop a quantum theory of dark solitons as finite-size quasiparticle excitations that experience superdiffusive spreading due to wave-packet dispersion. The small number of parameters relevant for the dynamics can be extracted from the yrast dispersion relation, i.e. the energy of lowest energy eigenstates at given momentum of the hosting quantum fluid. A soliton phase step is defined and demonstrated to provide logical consistency and the leading finite-size corrections with observable consequences for the energetics and dynamics in ring traps, even in strongly correlated low-dimensional systems where a superfluid order parameter may not exist. The theory is applied to the one-dimensional Bose gas in the Lieb-Liniger model where quantitative test with time-dependent quantum simulations based on Bethe-ansatz solutions corroborate the predictions of the theory. Experimental tests could be performed with ultra-cold atomic gases.

Application of the Full Configuration Interaction Quantum Monte Carlo method to ultracold atomic systems

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Ulrich Ebling
Massey University

The unitary Fermi gas is a regime where the interaction range is effectively zero and the scattering length diverges. The system is strongly correlated and Fermion pairing becomes very important. Quantum Monte Carlo methods applied to such systems suffer from the fermion sign problem. We adapt a rather recently developed method, Full Configuration Interaction Quantum Monte Carlo (FCIQMC) to obtain the ground state of the unitary, or more generally strongly correlated Fermi gas. FCIQMC was developed in the quantum chemistry community to describe many-body systems of strongly correlated electrons interacting via repulsive long-range Coulomb interactions. We have adapted FCIQMC to describe systems of strongly-interacting ultracold Fermions. FCIQMC addresses the sign problem in two ways. First it works in a Hilbert space built of Slater determinants, so the obtained ground state wave function is by construction fully antisymmetric. Second, it finds the ground state in this space using population dynamics of random walkers, which can have different signs, where the crucial step is that walkers of opposite sign annihilate each other. We use the Bertsch parameter, the ratio of the ground state energy of the unitary system and the non-interacing case, as a first benchmark and discuss advantages and disadvantages of FCIQMC in the context of ultracold atoms.

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Accelerating the basis set convergence in Full Configuration Interaction Quantum Monte Carlo for ultracold fermions

Peter Jeszenszki
Massey University

The objective of our project is to increase the accuracy of the ground state calculations of ultracold Fermi gases by applying a recently developed approach called Full Configurational Interaction Quantum Monte Carlo method (FCIQMC). Full Configurational Interaction implies that the wavefunction is expanded in a Slater determinant basis, while Quantum Monte Carlo stochastically propagates the wavefunction in imaginary time to determine the ground state solution. The Slater determinant representation in conjunction with the spontaneous emergence of stable phase relations circumvents the fermionic sign problem and thus facilitates the treatment of complex Fermi systems. However, this representation assumes the finite basis approximation, which leads to severe convergence properties in the strongly interacting regime. Most of the difficulties come from the reason that the one-particle basis cannot approximate efficiently the region when two particles are close to each other. We applied a so-called transcorrelated method, where the wavefunction is considered as a product of a Jastrow-type wavefunction and the linear combination of Slater-determinants. The Jastrow-type wavefunction captures the short-distance behavior of the particles, and it can be transformed into the Hamiltonian leaving a transcorrelated wavefunction, which can be calculated easier with finite basis expansion. We derived the Jastrow-factors in one- and three-dimensions in a way to satisfy Bethe-Peierls boundary conditions and examined the convergence properties in plane wave basis.

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Non-equilibrium dynamical phases from parametric instabilities in a driven-dissipative BEC in a cavity

Paolo Molignini
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In recent years, Bose-Einstein condensates in high-finesse optical cavities have been the subject of intense investigation for their ability to experimentally realize exotic quantum phase transitions, such as the Dicke phase transition from a normal to a superradiant phase via self-organization or a transition to a lattice supersolid phase when the system interacts with an optical lattice. In our work, we investigate the effect of parametric driving on such systems and its implications on the mapping to the Dicke model. We simulate the full time-evolution of such driven-dissipative systems with the multi-configurational time-dependent Hartree method (MCTDH), calculate stability diagrams and various many-body observables beyond mean-field approximations. In the Dicke scenario, in addition to the established normal and superradiant phases, the system displays a third nonequilibrium phase. This dynamical normal phase is macroscopically characterized by a complex density reorganization which leads to a switching between two symmetry-broken superradiant configurations. We extract information about cavity fluctuations and analyze the behavior of the dynamical normal phase as a function of various parameters. On the basis of a mapping to an effective driven-dissipative Dicke model, we predict the regimes of the novel phase and relate it to the phenomenon of many-body parametric resonance. The new phase exhibits also intriguing heating properties. In particular, we find that the periodically modulated system can thermalize only in this novel phase, indicating a crossover between integrability and non-integrability.

Semi-classical approaches to quantum many-body dynamics on lattices

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Novel experiments with ultracold atoms offer platforms for studying non-equilibrium dynamics of large quantum many-body lattice models in controlled environments. Thus, also numerical methods for simulating such dynamics are of great importance. While in 1D techniques based on matrix product states have been very successful, computing dynamics in higher dimensions remains to be a challenge. Here, I present the DTWA, a semi-classical method based on the well-known truncated Wigner approximation. This method has been surprisingly successful in predicting dynamics of lattice spin-1/2 models, particularly in high dimensional systems. I show how this method can be generalized to study dynamics of arbitrary discrete lattice models.

Light-induced enhancement of charge transport

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The transport properties of electrons are theoretically studied in a one-dimensional setup, when inter-band transitions couple to the light field of a cavity mode that is close to its vacuum. It is shown that light-matter interaction can allow for a significant enhancement of steady-state charge currents in two bands that interact via emission and absorption of dressed photons. The analysis is performed by using non-equilibrium Green's function methods and quantum Master equation techniques. Moreover, we study the interplay between localization and cavity-enhanced transport in disordered lattice models. Here, the focus lies on the change of the diffusion properties for electrons/holes due to light-matter coupling, for which we show first results.

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Spatial effects in two-atom collective light scattering

Petra Fersterer
Otago University

Collective near resonant light scattering from a coherently driven ensemble of atoms has been much studied, but remains a problem of current interest, with recent experiments in dense clouds stimulating interest in theoretical analysis. The problem is challenging because each atom interacts both with the driving field and the field scattered by all its surrounding neighbours. The observable light field thus depends (for N atoms) on atom-atom correlations up to N-th order. The general problem is nonlinear and quickly becomes computationally intractable as the number of atoms increases. Therefore one must either restrict the probe intensity to be within the linear response regime or limit the system to a small number of atoms. We consider the latter case, with two atoms separated by less than a few wavelengths, each with a $j_l = 0$ to $j_u = 1$ atomic transition probed by a single mode CW laser.

We study the spatial distribution of the total intensity scattered at a large distance from the cloud, which forms a fringe pattern arising from the atomic spatial correlation. This distribution is completely characterised by three parameters: the peak scattered intensity (typically found in the forward direction), the visibility of the spatial fringes, and the phase of the atomic spatial correlation. We have developed a physical interpretation of the system behaviour by considering the effective field at each atom arising from the interference of the laser field and light scattered by the other atom. This effective field interpretation is valid for interatomic distances greater than one wavelength and provides a physical understanding of how both the maximum intensity and visibility of the fringes change with the magnitude and direction of the interatomic distance, and laser intensity.

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Self-similar dynamics in a one-dimensional spinor Bose gas

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After a quench a non-integrable many-particle system will eventually relax back to its thermal state. However, on the route to thermalization universal dynamics characterized by temporal rescaling of spatial correlation functions may be encountered, a phenomenon known as a non-thermal fixed point. We access and study this regime theoretically employing a spinor Bose-Einstein condensate in one spatial dimension with ferromagnetic interactions. We prepare our system in the polar phase and quench into the symmetry-broken ferromagnetic phase. After a build-up of excitations in the transversal spin we observe self-similar evolution, which is due to the non-linear redistribution of excitations among different momenta. We determine the emerging scaling form for the structure factor of the transversal spin and extract the set of corresponding scaling exponents.

Spatially distributed multipartite entanglement enables Einstein-Podolsky-Rosen steering of atomic clouds

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Entanglement is systems of indistinguishable particles can be harnessed for quantum enhanced metrology. Yet, the robust generation and detection of entanglement between spatially separated regions of an ultracold atomic system remains a challenge. Whether such entanglement can ever serve as resource for quantum information tasks has in fact been the subject of a long-standing debate. I report on an experiment where we use spin mixing in a tightly confined Bose-Einstein condensate to generate an entangled state of indistinguishable particles in a single spatial mode. We show that this entanglement can be spatially distributed by self-similar expansion of the atomic cloud. Spatially resolved spin read-out is used to reveal a particularly strong form of quantum correlations known as Einstein-Podolsky-Rosen steering between distinct parts of the expanded cloud, directly verifying the usefulness of the generated entanglement for certain quantum cryptography tasks. Based on the strength of Einstein-Podolsky-Rosen steering we construct a witness, which testifies up to genuine five-partite entanglement.

Spatial entanglement patterns and Einstein-Podolsky-Rosen steering in a Bose-Einstein condensate

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We investigate the spatial entanglement in a spin squeezed Bose-Einstein condensate of rubidium atoms. By letting the atomic cloud expand and using high resolution absorption imaging we are able to access the spatial spin distribution of the many-body state. The observed spin correlations between different regions go beyond classical correlations and reveal spatial non-separability. Furthermore they allow for EPR steering of a subregion of the atomic spin. By inferring measurement outcomes of non-commuting observables in one region based on measurements in a separate region we are able to seemingly beat the Heisenberg uncertainty relation, realizing the EPR paradox with an atomic system. Our findings could be relevant for future quantum enhanced measurements of spatially varying observables such as electromagnetic fields.

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