UBEC 2019

April 1–5, 2019
Twentieth Century Club
Pittsburgh, PA

UNIVERSAL THEMES OF BOSE-EINSTEIN CONDENSATION

	Monday April 1	Tuesday April 2	Wednesday April 3	Thursday April 4	Friday April 5
	Chair: Snoke	Chair: Ketterle	Chair: V. Liu	Chair: Campbell	Chair: Szymanska
9:00 am - 9:45 am	*Svistunov*	*Szymanska*	*Shin* *Jin*	*Khoury*	*Ketterle*
9:45 am - 10:30 am	*Halperin*	*Pieczarka* *Ballarini*	*Trivedi*	*Hui*	*Kirton*
10:30 am - 10:50 am	*coffee break*	*coffee break*	*coffee break*	*coffee break*	*coffee break*
10:50 am - 11:10 am	*Levy*	*Kanai*	*Rontani*	*Boyanovksy*	*Walker*
11:10 am - 11:30 am	*Kuznetsov*	*Proukakis*	*Huang*	*Scully*	*Kurtscheid*
11:30 am - 11:50 am	*Briggeman*	*Salman*	*Giamarchi*		*Yoon*
11:50 am - 12:35 am	*Demler*	*Groszek*	*Ruegg*	*Box Lunch* *12:00 PM*	*Siemens*
12:35 pm - 2:00 pm	*lunch*	*lunch*	*lunch*	*Depart at* *12:15 PM* *for* *Fallingwater* *Depart at* *1:00 PM* *for* *Frick House* *or* *Warhol* *Museum*	*lunch*
	Chair: M. Chan	Chair: Fetter	Chair: Halperin		Chair: Proukakis
2:00 pm - 2:45 pm	*Fetter*	*Rey*	*Abbamonte*		*Campbell*
2:45 pm - 3:30 pm	*Guo*	*Lin*	*Bailey*		*Cabrera*
3:30 pm - 3:50 pm	*coffee break*	*coffee break*	*coffee break*		*coffee break*
3:50 pm - 4:35 pm	*Smith*	*Poster* *Session* *4:00 PM - 6:00 PM*	*Bill Phillips* *Alumni Hall* *4:00 PM*		*Langen* *Akimov* *Quader*
4:35 pm - 5:25 pm	*Lebreuilly*				
5:25 pm - 5:45 pm	*Mukherjee*				*Closing*
7:30 PM				*Conference* *Banquet* *7:30 PM - 10:00 PM*	

Pittsburgh - Oakland

See and Do

1. Rodef Shalom Synagogue
2. Schenley Plaza
3. Flagstaff Hill
4. Phipps Conservatory
5. Soldiers and Sailors Museum
6. Carnegie Library
7. Carnegie Museums
8. Cathedral of Learning
9. Heinz Memorial Chapel
10. Stephen Foster Memorial
11. Forbes Field/Posvar Hall
12. Frick Fine Arts Building
13. William Pitt Union
14. Alumni Hall
15. Salk Hall
16. Petersen Events Center
17. The Cut
18. Miller Gallery
19. Hammerschlag Hall
20. Wean Hall
21. Newell-Simon Hall
22. College of Fine Arts
23. Posner Center
24. Margaret Morrison Hall
25. The Frame

Eat

1. Essie's Original Hot Dog Shop ("The O")
2. Dave & Andy's Ice Cream
3. Uncle Sam's Subs
4. Union Grill
5. Primanti Brothers
6. Taiwan Cafe
7. India Garden
8. Star of India
9. Mad Mex
10. Veracruz
11. Fuel & Fuddle

Buy

1. Caliban Book Shop
2. Jay's Bookstall
3. Pitt Book Center
4. The Pitt Shop

Drink

1. Hemingways
2. Gene's Place

Sleep

1. Wyndham Hotel
2. Hilton Garden Hotel
3. Quality Inn
4. Hampton Inn

Monday

Talks

The Halon: A Quasiparticle Featuring Critical Charge Fractionalization

Boris Svistunov [1,2,3], **Kun Chen** [1,4], **Yuan Huang** [1], **Youjin Deng** [5]

[1]**University of Massachusetts**
666 N. Pleasant St., Amherst MA 01003, USA

[2]**National Research Center "Kurchatov Institute"**
123182 Moscow, Russia

[3]**Wilczek Quantum Center**
Shanghai Jiao Tong University, Shanghai 200240, China

[4]**Rutgers, The State University of New Jersey**
Piscataway, NJ 08854-8019, USA

[5]**University of Science and Technology of China**
Hefei, Anhui 230026, China

The halon is a special critical state of an impurity in a quantum-critical environment. The hallmark of the halon physics is that a well-defined integer charge gets fractionalized into two parts: a microscopic core with half-integer charge and a critically large halo carrying a complementary charge of $\pm 1/2$. The halon phenomenon emerges when the impurity - environment interaction is fine-tuned to the vicinity of a boundary quantum critical point (BQCP), at which the energies of two quasiparticle states with adjacent integer charges approach each other. The universality class of such BQCP is captured by a model of pseudo-spin-1/2 impurity coupled to the quantum-critical environment, in such a way that the rotational symmetry in the pseudo-spin *xy*-plane is respected, with a small local "magnetic" field along the pseudo-spin *z*-axis playing the role of control parameter driving the system away from the BQCP. On the approach to BQCP, the half-integer projection of the pseudo-spin on its *z*-axis gets delocalized into a halo of critically divergent radius, capturing the essence of the phenomenon of charge fractionalization. With large-scale Monte Carlo simulations, we confirm the existence of halons—and quantify their universal features—in O(2) and O(3) quantum critical systems.

The O(2) halon problem in (2 + 1)D has a 3D counterpart in terms of quantized magnetic flux generated by a solenoid introduced into a superconductor at its critical temperature. The flux-loop model (a.k.a. frozen lattice superconductor) with a quasi-solenoid perturbation is the model of choice for qualitative and quantitative description of both the halon and the magnetohalon effects.

References

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Chiral Superfluids and Superconductors

William Halperin
Northwestern University
2145 Sheridan Rd., Evanston IL, USA

New anisotropic states of superfluid ^{3}He have been studied at Northwestern University similar to those in a number of superconducting compounds, like UPt_3 and Sr_2RuO_4. I will discuss and compare three unconventional superconducting materials for which measurements of physical properties indicate unconventional order parameter symmetries, most importantly chiral symmetry and broken time reversal symmetry, clearly in evidence in high quality single crystals of the *f*-wave superconductor UPt_3, the *p*-wave superfluid ^{3}He, and ^{3}He in highly porous silica aerogel.[1]

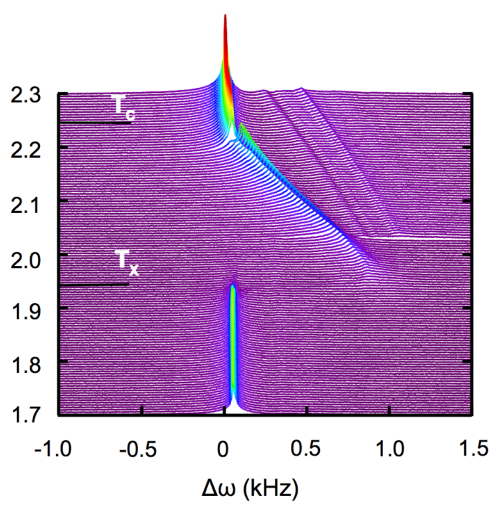

Figure 1. New results on the NMR spectrum of superfluid ^{3}He-B at P = 27 bar, in a globally uniform, anisotropic, silica aerogel reveal a spontaneous 90° reorientation of the angular momentum in a reversible thermodynamic phase transition at temperature T_x (mK vertical scale).[4]

All of these systems have multiple thermodynamic phases, with different order parameter structure. In this context, theoretical predictions indicate that anisotropic quasiparticle scattering favors stability of anisotropic quantum states.[2] In particular we have shown that this is the case for chiral states of superfluid ^{3}He confined to uniformly anisotropic silica aerogel,[3] and as shown in the recently discovered orbital-flop phase, Fig. 1.[4] This is also apparent in UPt_3 and can be attributed to anisotropic impurities associated with prism-plane stacking faults.

Superfluids and superconductors having vector order parameters with a continuous symmetry are expected to lose long range coherence in the presence of disorder according to Imry and Ma.[5] We have demonstrated this phenomenon in superfluid ^{3}He-A in an isotropic silica aerogel, and it is also the likely mechanism for the highly unusual time dependent disorder in the superconducting vortex lattice of UPt_3 observed with small angle neutron scattering.

Acknowledgements
I am grateful to many students. Those currently at Northwestern are A.M. Zimmerman, M.D. Nguyen, J.W. Scott, K.E. Avers; and to collaborators J. A. Sauls, M.R. Eskildsen, D.J. Van Harlingen and A. Kapitulnik. Support for this work is from the NSF, CMP Program, grant No. DMR-1602542 (^{3}He) and the DOE/BES CMP program DE-FG02-05ER46248 (UPt_3)

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Electron Pairing Without Superconductivity

Guanglei Cheng, Michelle Tomczyk, Shicheng Lu, Joshua P. Veazey, Mengchen Huang, Patrick Irvin, Sangwoo Ryu, Hyungwoo Lee, Chang-Beom Eom, C. Stephen Hellberg, Jeremy Levy

[1]**Pittsburgh Quantum Institute,** 3943 O'Hara St., Pittsburgh, PA 15260 USA
[2]**University of Pittsburgh,** 3941 O'Hara St., Pittsburgh, PA 15260 USA
[3]**University of Wisconsin-Madison,** Madison, WI 53706 USA
[4]**Naval Research Laboratory,** Washington DC 20375, USA

Strontium titanate ($SrTiO_3$) is the first and best known superconducting semiconductor [1]. It exhibits an extremely low carrier density threshold for superconductivity, and possesses a phase diagram similar to that of high-temperature superconductors—two factors that suggest an unconventional pairing mechanism. Despite sustained interest for 50 years, direct experimental insight into the nature of electron pairing in $SrTiO_3$ has remained elusive. Here we perform [2] transport experiments with nanowire-based single-electron transistors at the interface between $SrTiO_3$, and a thin layer of lanthanum aluminate $LaAlO_3$. Electrostatic gating reveals a series of two-electron conductance resonances—paired electron states—that bifurcate above a critical pairing field B_p of about 1–4 tesla, an order of magnitude larger than the superconducting critical magnetic field. For magnetic fields below B_p, these resonances are insensitive to the applied magnetic field; for fields in excess of B_p, the resonances exhibit a linear Zeeman-like energy splitting. Electron pairing is stable at temperatures as high as 900 millikelvin, well above the superconducting transition temperature (about 300 millikelvin). These experiments demonstrate the existence of a robust electronic phase in which electrons pair without forming a superconducting state. Key experimental signatures are captured by a model involving an attractive Hubbard interaction that describes real-space electron pairing as a precursor to superconductivity.

Figure 1. Artist's rendition of three distinct electronic phases in $SrTiO_3$ (top to bottom): normal, paired non-superconducting, and superconducting.

Acknowledgements

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Long-range non-difusive spin transfer in a Hall insulator

V. A. Kuznetsov[1, 2], **L. V. Kulik**[2], **A. S. Zhuravlev**[2], **A. V. Gorbunov**[2], **I. V. Kukushkin**[1, 2]
[1]**National Research University Higher School of Economics**
20 Myasnitskaya Street, Moscow, Russia
[2]**Institute of Solid State Physics**
2 Academician Ossipyan Street, Chernogolovka, Russia

It's known that the excitons are unstable in metals, such as 2D-electron gas. However, in quantizing magnetic field and at temperature below the cyclotron quantization energy, a 2D metal turns into a special type of 2D insulator at even integer quantum Hall states. Excitations in quantum Hall insulators are magnetoexcitons. The simplest realizations are magnetoexcitons formed by an electron promoted from the occupied zeroth Landau level to the empty first Landau level and by the vacancy under the Fermi level at the filling factor of 2. There are two magnetoexcitons: a spin singlet with total spin $\mathbf{S} = 0$; and a spin triplet with total spin $\mathbf{S} = 1$ and spin projections along the magnetic field axis $\mathbf{S_z} = -1, 0, 1$. The singlet magnetoexciton $\mathbf{S} = 0$ is magnetoplasmon which decays with emission of a photon. In contrast, the spin-triplet magnetoexciton is not radiatively active owing to electron spin conservation. The many-body Coulomb interaction lowers its energy below the cyclotron energy. Thus, the spin-triplet magnetoexciton is an excited state with the lowest energy. Consequently, spin-triplet magnetoexcitons exhibit relaxation time reaching hundreds of microseconds [1].
An experimental technique for the creation, manipulation, and detection of macroscopic ensembles of spin-triplet magnetoexcitons has been developed. The ensemble can be created with a resonant optical excitation. Furthermore, we discovered condensation of excitons by time-resolved measurements of exciton lifetime in a temperature range of 0.5–1.5 K [2]. Here we report on spin exciton transfer at distance exceeding 200 µm by pump-probe photoluminescence measurements and photo-resonant reflection (PRR) [3]. These effects exhibit threshold both in excitation power and temperature.

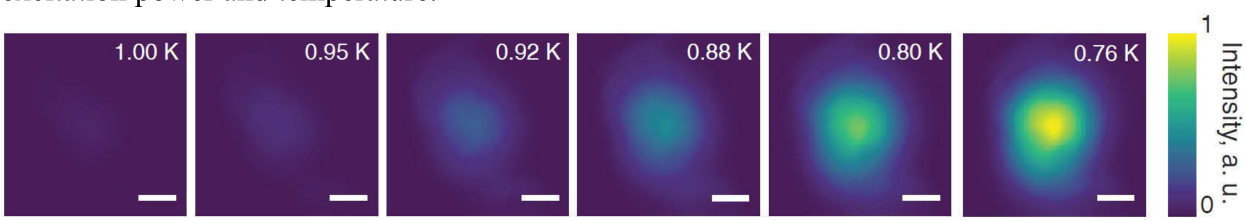

Figure 1. Evolution of the magnetoexciton condensate area with temperature visualized by PRR.

Acknowledgements
This work has been sponsored by the Basic research program of HSE.

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Pascal-liquid phases in ballistic one-dimensional $LaAlO_3/SrTiO_3$ channels

Megan Briggeman[1,2], Michelle Tomczyk[1,2], Binbin Tian[1,2], Hyungwoo Lee[3], Jung-Woo Lee[3], Yuchi He[2,4], Anthony Tylan-Tyler[1,2], Mengchen Huang[1,2], Chang-Beom Eom[3], David Pekker[1,2], Roger S. K. Mong[1,2], Patrick Irvin[1,2], Jeremy Levy[1,2]

[1]**Department of Physics and Astronomy, University of Pittsburgh**
Pittsburgh, PA 15260, USA
[2]**Pittsburgh Quantum Institute**
Pittsburgh, PA 15260, USA
[3]**Department of Materials Science and Engineering, University of Wisconsin-Madison**
Madison, WI 53706, USA
[4]**Department of Physics, Carnegie Mellon University**
Pittsburgh, PA 15213, USA

The challenge of understanding strongly interacting composite fermionic phases of matter spans many fields in physics, ranging from neutron stars to solid-state materials to quark-gluon plasmas. We report experimental evidence of a new family of degenerate quantum liquids formed from bound states of $n = 2, 3, 4, \ldots$ electrons, which are stabilized by attractive interactions within quasi-one-dimensional electron waveguides formed at the $LaAlO_3/SrTiO_3$ interface[1]. The key signature of this phase is the existence of quantized conduction that follows a characteristic sequence within Pascal's triangle: $(1, 3, 6, 10, 15, \ldots) \cdot e^2/h$, where e is the electron charge and h is the Planck constant. The ability to create and investigate composite fermionic phases opens new avenues for the investigation of strongly correlated quantum matter.

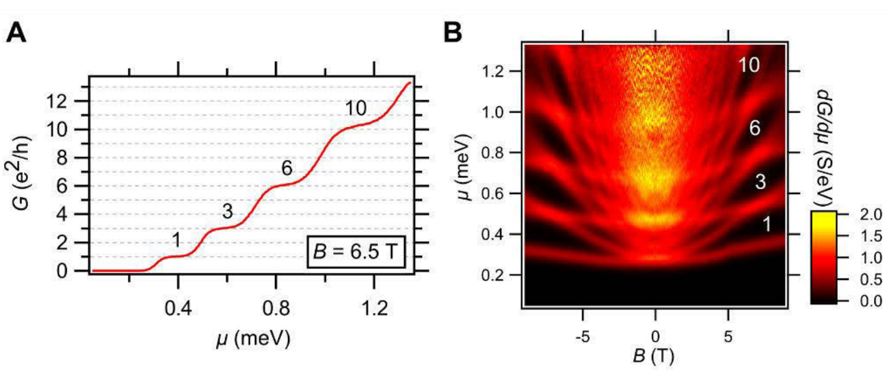

Figure 1: **(A)** Pascal series of conductance steps in an electron waveguide. **(B)** Transconductance data for an electron waveguide device as a function of applied magnetic field B, and chemical potential μ. Bright regions indicate increasing conductance as new subbands become occupied, and dark regions indicate conductance plateaus. The transconductance map shows the locking of increasing numbers of subbands and the corresponding conductance plateau values. The locking of subbands indicates the formation of bound states of $n \geq 2$ electrons.

Acknowledgements

This work is supported in part by a Vannevar Bush Faculty Fellowship ONR grant N00014-15-1-2847 (J.L.) and the Charles E. Kaufman Foundation (D.P). The work at University of Wisconsin-Madison (design and synthesis of thin film heterostructures) was supported by the US Department of Energy (DOE), Office of Science, Office of Basic Energy Sciences, under award number DEFG02-06ER46327.

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New perspectives on quantum matter: bringing together quantum simulations and machine learning

Eugene Demler, Harvard University

Abstract:

What can we learn about a many-body system when we measure every constituent particle? Current experiments with ultracold atoms provide snapshots of many-body states with single particle resolution. This calls for new approaches to studying quantum many-body systems with a focus on analyzing patterns and using machine learning techniques. I will present a recent application of this method to study magnetic polarons in antiferromagnetic Mott insulators. Results indicate that magnetic polarons can be accurately described as spinon-chargon pairs bound by geometric strings, in close analogy to quark-antiquark bound pairs forming mesons in QCD. I will also discuss application of neural networks to compare different microscopic theories of doped Mott insulators.

Quantized superfluid vortex dynamics on curved surfaces

Alexander L. Fetter

Stanford University
GLAM, 476 Lomita Mall, Stanford, CA , USA

Superfluid flow on a cylindrical surface differs significantly from that on an infinite plane because of the additional winding number around the cylinder. The requirement that the condensate wave function be single valued means that a single vortex cannot be stationary; instead it acquires one of two quantized velocities around the circumference. The resulting phase pattern on an infinite cylinder illustrates the effect of the motion compared to that of a stationary vortex. The associated stream function also differs significantly from that on a plane; it has two topologically distinct types of trajectories (closed and open), analogous to the libration and rotation of a simple pendulum with increasing energy. In addition, the stream function determines the interaction energy of a vortex dipole (with opposite signs). Motion on a semi-infinite cone involves similar dynamics.

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Visualization study of quantum fluid dynamics in superfluid ^{4}He

Wei Guo[1,2]

[1]**National High Magnetic Field Laboratory**
1800 East Paul Dirac Drive, Tallahassee, FL 32310, USA
[2]**Mechanical Engineering Department**
Florida State University, Tallahassee, FL 32310, USA

Helium-4 in the superfluid phase (He II) is a two-fluid system that exhibits fascinating quantum fluid dynamics with important scientific and engineering applications. It supports the most efficient heat-transfer mechanism (i.e. thermal counterflow), and it also allows the generation of flows with extremely high Reynolds numbers for turbulence modelling. However, the lack of high-precision flow measurement tools in He II has impeded the progress in understanding and utilizing its hydrodynamics. In recent years, there have been extensive efforts in developing quantitative flow visualization techniques applicable to He II [1]. Two types of techniques based on the use of either particle tracers (i.e. micron-sized frozen particles) or molecular tracers (i.e. He_2^* excimer molecules) have been developed. We will discuss the advantages and issues associated with these visualization techniques and will highlight some recent progresses in our visualization study of counterflow and quasiclasscial turbulence in He II [2-4]. We will also briefly introduce our on-going work on developing the next generation flow visualization techniques and our effort on imaging quantized vortices in a levitated drop of He II.

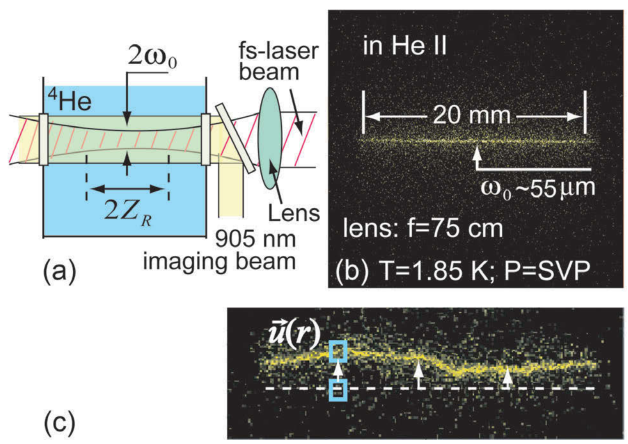

Figure 1: (a) Schematic diagram showing the optical setup for creating and imaging He_2^* molecular tracer lines in helium. (b) A typical tracer line image in He II upon its creation. (c) Schematic showing how the local velocity can be calculated. The dashed line indicates the tracer line initial location.

Acknowledgements

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Strongly interacting homogeneous Bose gases

Robert Smith[1,2]

[1]University of Oxford
Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK.
[2] (previously) University of Cambridge
Cavendish Laboratory, J.J. Thomson Avenue, Cambridge, CB3 0HE, UK.

I will give an overview of our recent work on strongly interacting homogenous Bose gases. Using a ^{39}K gas confined in an optical box potential we have:

(a) Quantitatively measured the interaction dependence of the quantum depletion of a Bose-Einstein condensate (BEC) and quantitatively confirmed Bogoliubov's 70 year old prediction [1].
(b) Shown that the excitation spectrum of a homogenous Bose gas begins to deviate from the classic Bogoliubov form for strong interactions in a way that hints at the appearance of a roton minimum [2].
(c) Explored the unitary regime (where the inter-particle interaction strength is as strong as allowed by quantum mechanics). Our work includes studies of atom loss, molecular correlation and momentum distribution dynamics. We find universal scalings of these observables across a wide range of parameter space and evidence for the emergence of a pre-thermal quasi-steady state with a finite condensed fraction [3, 4].

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R. Lopes, C. Eigen, A. Barker, K. G. H. Viebahn, M. Robert-de-St.-Vincent, N. Navon, Zoran Hadzibabic, and Robert P. Smith,
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Phys. Rev. Lett. **118**, 210401 (2017).

Quantum fluids of light: from superfluidity to strong correlations

Josè Lebreuilly, Yale University

Abstract:

In this talk I will review the theoretical and experimental aspects of quantum fluids of light, where large ensembles of photons are brought to develop quantum many-body behaviours in virtue of the optical nonlinearity of an underlying medium. In a first part I will introduce the physics of polaritons in semiconductor microcavities, and give an overview of the early experiments on Bose-Einstein condensates and superfluids, as well as more recent developments on photonic simulators in micropillar lattice architectures. In a second part, I will present the last advances on the preparation of strongly correlated quantum phases where photons behave as impenetrable particles, including the dissipative stabilization of a photonic Mott Insulator, along with promising steps towards Fractional Quantum Hall states of light.

Natural Oscillations of a Polariton Condensate in a Ring

S. Mukherjee,[1] D. M. Myers,[1] R.G. Lena,[2] B. Ozden,[3] J. Beaumarriage,[1] Z. Sun,[1] M. Steger,[4] L. N. Pfeiffer,[5] K. West,[5] A. J. Daley[2] and D. W. Snoke[1]

[1]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
[2]Department of Physics and SUPA, University of Strathclyde, Glasgow G4 0NG, United Kingdom
[3]Department of Physics and Engineering, Penn State Abington, Abington, PA 19001, USA
[4]National Renewable Energy Lab, Golden, CO 80401, USA
[5]Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA

We have observed oscillations of a polariton condensate in a quasi-one-dimensional ring geometry that correspond to the natural frequency of a rigid pendulum. Time-resolved measurements allow us to make spatially- and spectrally-resolved movies of the oscillation over hundreds of picoseconds. The results are modeled by a Gross-Pitaevskii equation with dissipation and decay. By comparing the oscillations in energy and density, we conclude that excitons have also traveled with the polaritons around the ring. We also show how the oscillations provide tighter constraints on the direct measurement of the polariton-polariton interaction strength, which is an important parameter for theories of nonlinear optics with polariton systems.

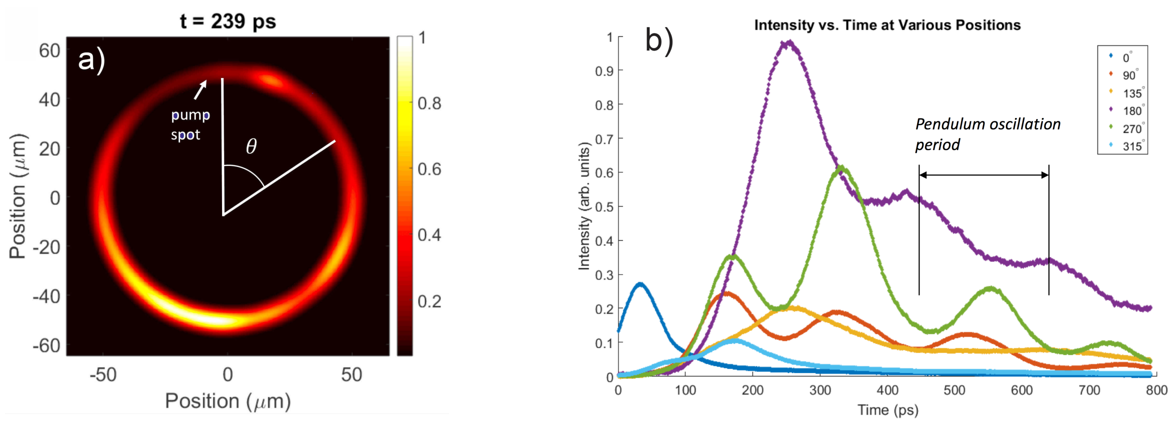

Figure 1. a) Snap shot from a movie (available at https://tinyurl.com/y97x7yap) of the polariton motion in a ring. b) The intensity as a function of time at various points on the ring, for a typical experiment.

Acknowledgements: Army Research Office (W911NF-15-1-0466). The work of sample fabrication at Princeton was funded by the Gordon and Betty Moore Foundation (GBMF-4420) and by the National Science Foundation MRSEC program through the Princeton Center for Complex Materials (DMR-0819860). Work at Strathclyde was supported by the EPSRC Programme Grant DesOEQ (EP/P009565/1). S.M. also acknowledges the support of the Pittsburgh Quantum Institute.

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Tuesday

Talks

Polariton quantum fluids in and out of equilibrium

M. H. Szymanska

Department of Physics and Astronomy, University College London, U.K.
E-mail: m.szymanska@ucl.ac.uk

State-of-the-art semiconductor microcavities allowed recently to achieve a fully thermalised photonic system analogous to cold atoms or liquid Helium. 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 (Fig. 1). 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]

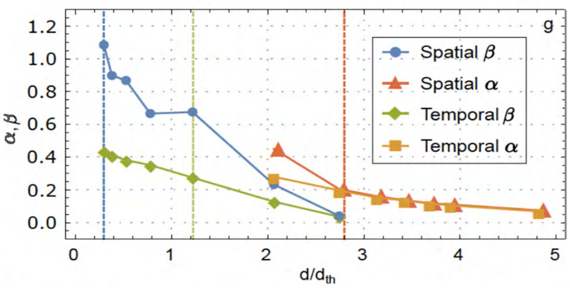
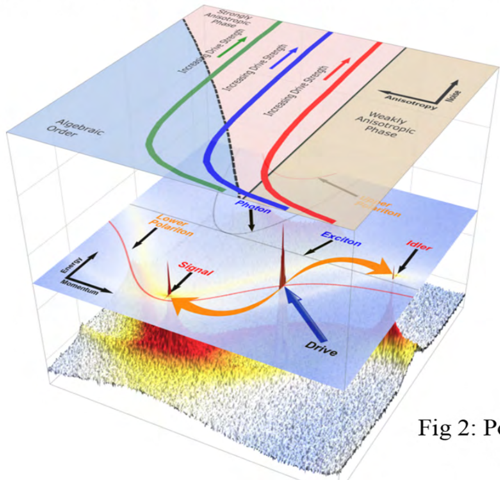
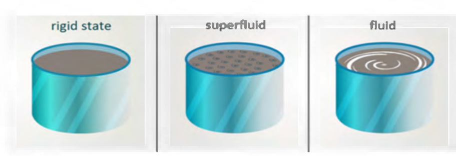


Fig 1: Exponents of spatial and temporal coherence.



At the same time, it has been shown that driven-dissipative polariton fluid could exhibit a 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 system in 2D and even 1D realisations are not conclusive. We show [2] that driven microcavity polaritons in the OPO configuration (Fig. 2) can act as a unifying laboratory for the exploration of a variety of intrinsic non-equilibrium phenomena, including the so far experimentally elusive KPZ phase in two dimensions.

Fig 2: Polariton OPO spectrum (bottom) and phase diagram (top).



Finally, we determine that the superfluid response—the difference between responses to longitudinal and transverse forces—is zero for *coherently* driven polaritons. This is a consequence of the gapped excitation spectrum caused by external phase locking. Furthermore, while a normal component exists at finite pump momentum, the remainder forms a rigid state that is unresponsive to either longitudinal or transverse perturbations and suggests that the suppression of scattering observed in experiments should be interpreted as a sign of a new rigid state of matter and not a superfluid.

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Quantum depletion of a trapped nonequilibrium exciton-polariton condensate

M. Pieczarka[1], E. Estrecho[1], M. Boozarjmehr[1], M. Steger[2], K. West[3], L. Pfeiffer[3], D. W. Snoke[4], A. G. Truscott[5], E. A. Ostrovskaya[1]

[1]**ARC Centre of Excellence FLEET and Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University,** Canberra ACT 2601, Australia
[2]**National Renewable Energy Lab,** Golden, CO 80401, USA
[3]**Department of Electrical Engineering, Princeton University,** Princeton, NJ 08544, USA
[4]**Department of Physics and Astronomy, University of Pittsburgh,** PA 15260, USA
[5]**Laser Physics Centre, Research School of Physics and Engineering, The Australian National University,** Canberra ACT 2601, Australia

Exciton-polariton condensates in semiconductor microcavities form a nonequilibrium bosonic quantum system with a spontaneously appearing macroscopic coherence. The quantum nature of exciton-polariton interactions has been shown recently on a single particle level [1].

In this work, we present experimental evidence of the quantum depletion [2] of a high density, optically trapped exciton-polariton condensate [3]. To gain access to a very weak signal of the excitation branches, we introduced an edge filter in a momentum space to block the signal from the condensate ground state, see Fig. 1a. We analyse the occupation of the excitation branches to deduce dominating populating mechanisms. The appearance of the ghost branch (GB) signal and characteristic algebraic decay of k-space occupation, according to Bogoliubov theory, confirm the quantum depletion of the condensate, Fig. 1b. We additionally study the interplay of different mechanisms responsible for populating the normal branch and discuss the crucial role of nonequilibrium effects in the high-density polariton condensate in contrast to the equilibrium Bose-Einstein condensates.

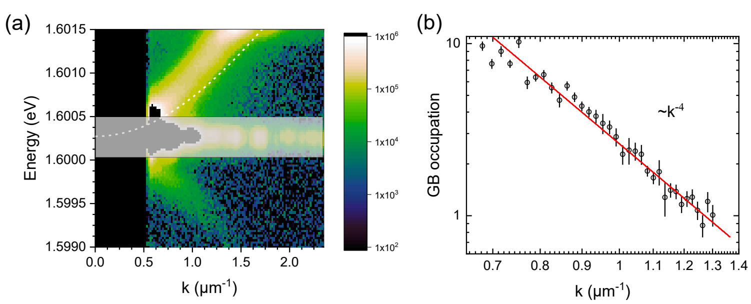

Fig. 1. (a) Momentum-space photoluminescence spectrum of excitation branches at high condensate density. Condensate emission is blocked with a momentum edge filter. Image is saturated and the colour scale is logarithmic. Dashed line shows a single-particle dispersion. Shaded rectangle indicates diffracted emission from the k=0 condensate. (b) Extracted occupation of quasiparticles in the ghost branch (GB) showing characteristic algebraic dependency.

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Excitations of long-lived polariton condensates

D. Ballarini[1], **D. Caputo**[1], **G. Dagvadorj**[2], **K. West**[3], **L. Pfeiffer**[3], **M. Matuszewski**[4], **M. H. Szimanska**[5], **D. Sanvitto**[1,6]

[1]**CNR-NANOTEC**
Via Monteroni, 73100 Lecce, Italy
[2]**Department of Physics, University of Warwick**
Coventry CV4 7AL, United Kingdom
[3]**PRISM, Princeton Unviversity**
Princeton, NJ 08540
[4]**Institute of Physics, Polish Academy of Sciences (PAN)**
02-668 Warszawa, Poland
[5]**Department of Physics and Astronomy, University College London**
Gower Street, London WC1E 6BT, United Kingdom
[6]**INFN**
Sez. Lecce, 73100 Lecce, Italy

Exciton-polaritons in semiconductor microcavities are composite bosons with the unique capability of forming non-equilibrium driven-dissipative condensates. Recently, in high quality factor microcavities, large polariton condensates have been shown to approach the same decay of coherence as a BKT phase of 2D interacting bosons [1,2]. Here we show that the dispersion of the excitation spectrum can be extracted from the information enclosed in the spatial and temporal correlations, demonstrating the linearization of the dispersion due to interactions. We demonstrate the effect of an asymmetric pumping configuration, which results in the formation of directional excitations in the condensate. Moreover, we show that topological excitations can be induced by imposing a twisted-phase boundary. A wide range of dynamical responses of the condensate is measured, spanning from the formation of a long phase-slip line to the nucleation of Josephson vortices within the barrier, until the recovering of the superfluid behavior at higher densities.

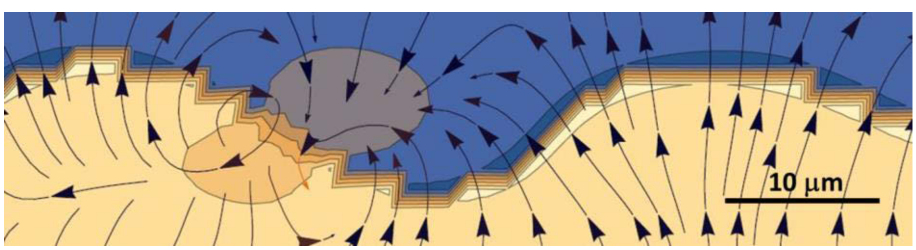

Figure 1: Phase jump between two spatially separated condensates and formation of vortices under an externally imposed, twisted-phase boundary condition.

Acknowledgements

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Angular momentum transfer due to non-topological phase defects during the merging of rotating Bose-Einstein condensates

<u>Toshiaki Kanai</u>[1,2], Wei Guo[1,3], Makoto Tsubota[4,5]

[1]National High Magnetic Field Laboratory (NHMFL)
1800 East Paul Dirac Drive, Tallahassee, FL 32310, USA
[2]Department of Physics, Florida State University
Tallahassee, FL 32306, USA
[3]Department of Mechanical Engineering, Florida State University
Tallahassee, FL 32310, USA
[4]Department of Physics, Osaka City University
3-3-138 Sugimoto, Sumiyoshi-Ku, Osaka 558-8585, Japan
[5]The OCU Advanced Research Institute for Natural Science and Technology (OCARINA), Osaka City University
Sumiyoshi-Ku, Osaka 558-8585, Japan

Merging of isolated Bose-Einstein condensates (BECs) is an important topic due to its relevance to matter-wave interferometry and the celebrated Kibble-Zurek mechanism. Many past research focused on merging of BECs with uniform initial phases. The situation is less clear when the condensates contain vortices and have non-uniform phases before merging occurs. In our recent study on 2-dimensional (2D) [1,2] and 3-dimensional (3D) BEC merging, we set two condensates separated by a wall potential initially, with one of them in rotation with quantized vortice and the other being static. During the condensate merging, we observe the emergence of spiral soliton lines (2D cases) or helical soliton sheets (3D cases) that enable the transfer of angular momentum between the condensates even in the absence of quantized vortices. A close examination of the flow field around the solitons strikingly reveals that their sharp endpoints (2D cases) or edge lines (3D cases) can induce flows like a vortex point or a vortex line but effectively with a fraction of a quantized circulation. These interesting nontopological phase defects may play important roles in many quantum transport processes.

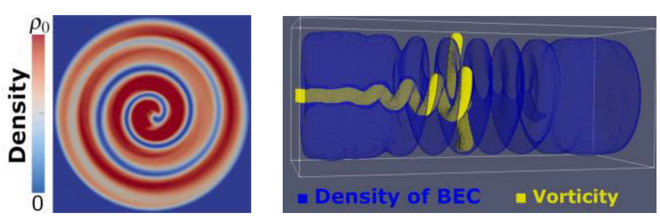

Figure 1: The appearance of a spiral soliton in 2D BEC (left one) and a helical soliton in 3D BEC (right one) during BEC merging.

Acknowledgements
W. G. and T. K. acknowledge the support by the National Science Foundation under Grant No. DMR1507386 and the support from the NHMFL, which is supported by NSF Grant No. DMR1644779 and the State of Florida. M. T. acknowledges the support by the Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant No. JP17K05548 and JP16H00807.

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Dynamical Phase Transition Crossing and Relaxation of Trapped Quantum Gases

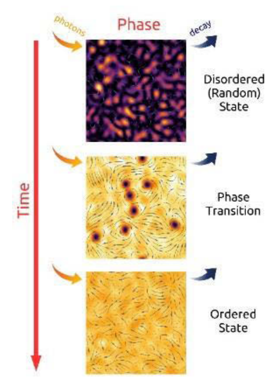
I Liu[1,2], P Comaron[1], G Dagvadorj[4], A Zamora[4], F Larcher[1,3], S Donadello[3], G Lamporesi[3], G Ferrari[3], SC Gou[2], I Carusotto[3], MH Szymanska[4], F Dalfovo[3] and NP Proukakis[1]

[1]Joint Quantum Centre (JQC) Durham-Newcastle, Newcastle University, UK
[2]National Changhua University of Education, Taiwan
[3]BEC Centre, Trento, Italy
[4]University College London, UK

The formation of an equilibrium state from an uncorrelated thermal one through the dynamical crossing of a phase transition is a widely-debated topic at the heart of quantum many-body physics. This crossing is facilitated by spontaneous breaking of system Hamiltonian symmetry, associated with the spontaneous emergence of defects in its density, as first raised by Kibble in the cosmological context, and subsequently applied to the condensed-matter realm by Zurek. Such predictions can be critically re-assessed in the context of quantum gases.

Firstly, we focus on a controlled gradual temperature quench across the Bose-Einstein condensation phase transition in an elongated 3D atomic condensate. Using stochastic numerical simulations we demonstrate [1] a clear visualization of the entire dynamical process, with spontaneous emergence of symmetry-breaking in the critical region, and excellent agreement with experimental observations. We demonstrate an explicit decoupling of the relevant timescales for number and coherence growth, arising from the interplay of the spontaneously-generated defects and their subsequent dynamics.

We also discuss instantaneous quenches in homogeneous 2D gases, where the Berezinskii-Kosterlitz-Thouless phase transition becomes relevant. We demonstrate that the system fulfills the dynamical scaling hypothesis, with a dynamical critical exponent z=2, consistent with the 2D XY model. We show that this holds for exciton-polaritons, despite their driven-dissipative nature [2], and demonstrate the feasibility of such observation in ultracold quasi-2D atomic boxes (e.g. Paris, Cambridge) with interaction quenches.



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EPSRC; QuantERA; AQuS; Autonomous Province of Trento, SiQuro; MOST (Taiwan)

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Long-range Ordering and Onsager Condensation of Topological Excitations in a Two-Dimensional Superfluid Far From Equilibrium

Hayder Salman* and Davide Maestrini
School of Mathematics, University of East Anglia,
Norwich Research Park, Norwich, NR4 7TJ, UK

In 2D atomic BECs, quasi long-range ordering and phase coherence is understood to arise from the Berezinski-Kosterless-Thouless transition that is associated with the binding of vortex and anti-vortex pairs. This transition permits superfluid flows to emerge in such systems that can support ensembles of a large number of vortices and anti-vortices with a characteristic healing length that is small relative to the inter-vortex separation. Under such conditions, the emergent superfluid flow can exhibit quasi-classical hydrodynamic characteristics [1]. In particular, like signed vortices can begin to cluster giving rise to a large scale coherent flow composed of many vortices within each cluster. This behaviour can be attributed to an emergent inverse energy cascade that leads to a so-called Onsager condensate. Therefore, in contrast to an inverse particle flux that leads to the emergence of a coherent matter wave, the 2D superfluid flow supports an inverse energy cascade that leads to spectral condensation of energy within the system.

We will report on numerical studies of the relaxation of a 2D ultracold Bose-gas from a nonequilibrium initial state consisting of vortices and antivortices in experimentally realizable square and rectangular traps that have been reported in [2]. We demonstrate how vortex clustering that arises can be understood in terms of negative temperature states of a vortex gas and we show that, within the negative temperature regime, an order parameter emerges that is related to the formation of long-range correlations between vortices. It turns out that the order parameter corresponds to the streamfunction of the 2D flow field that is governed by a Boltzmann-Poisson equation [3]. This equation describes the emergent coherent flow associated with the spectral condensation of energy in 2D superfluid flows and is associated with the emergence of a mean rotational hydrodynamic flow with a non-zero coarse-grained vorticity field. Solutions of the Boltzmann-Poisson equation in a square domain reveal a diverse family of possible solutions. These mean-field predictions are verified through direct simulations of a point vortex gas and 2D simulations of the Gross-Pitaevskii equation. Due to the long-range nature of the Coulomb-like interactions in point vortex flows, the negative temperature states strongly depend on the shape of the geometry [3]. As a further extension of these results, we analyse the spectra of the flow in the vortex clustered regime and relate these to the theory of non-thermal fixed points [4] and the theory of Kraichnan for inverse energy cascades in 2D fluid turbulence .

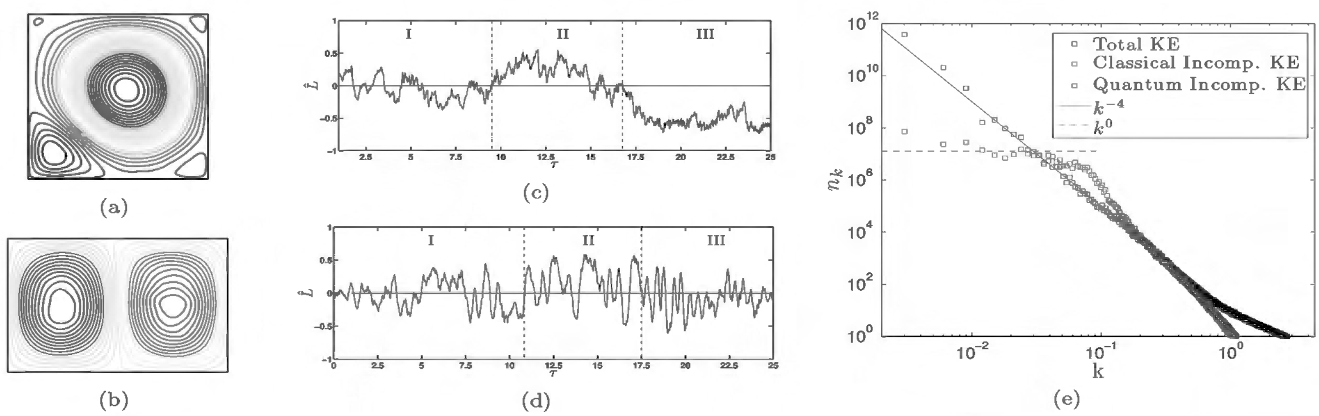

FIG. 1. Time averaged streamlines of numerical simulations at late times for (a) Square domain showing monopole mean flow structure and (b) Rectangular domain showing dipole mean flow structure; Angular momentum for (c) Square domain showing spontaneous acquisition of angular momentum and (d) Rectangular domain showing zero angular momentum at long times; (e) Occupation number spectra. Plots taken from results published in [3].

* H.Salman@uea.ac.uk
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Emergence of large-scale flow from turbulence in a two-dimensional superfluid

Shaun P. Johnstone[1], Andrew J. Groszek[1,2], Philip T. Starkey[1], Christopher J. Billington[1,3], Tapio P. Simula[1,4], Kristian Helmerson[1,5]

[1]School of Physics and Astronomy, Monash University
Victoria 3800, Australia
[2]Joint Quantum Centre Durham–Newcastle, School of Mathematics, Statistics and Physics, Newcastle University
Newcastle upon Tyne NE1 7RU, United Kingdom
[3]Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland
Gaithersburg, Maryland 20899, USA
[4]Centre for Quantum and Optical Science, Swinburne University of Technology
Victoria 3122, Australia
[5]ARC Centre of Excellence in Future Low-Energy Technologies, Monash University
Victoria 3800, Australia

Non-equilibrium interacting systems can evolve to exhibit large-scale structure and order. In two-dimensional turbulent flow the seemingly random swirling motion of a fluid can evolve towards persistent large-scale vortices. To explain such behavior, Lars Onsager [1] proposed a statistical hydrodynamic model based on quantised vortices. Our work provides an experimental confirmation of Onsager's model [2]. We drag a grid barrier through an oblate superfluid Bose–Einstein condensate to generate non-equilibrium distributions of vortices. We observe signatures of an inverse energy cascade driven by the evaporative heating of vortices [3], leading to steady-state vortex configurations characterised by negative absolute temperatures [1]. We measure these temperatures directly using our recently developed thermometry technique for two-dimensional superfluid turbulence [4]. Complementary observations of negative temperature vortex states have also recently been presented in a similar experiment by Gauthier et al. [5].

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New direction on quantum simulations with long-lived strontium dipoles in a cavity

<u>Ana Maria Rey</u>
NIST, JILA, and Physics Department, University of Colorado, Boulder, USA
Boulder, USA

Laser cooled and quantum degenerate atoms are widely being pursued as quantum simulators that may explain the behavior of strongly correlated material systems, and as the basis of today's most precise sensors. A key task to achieve these goals is to understand and control coherent interactions between the atoms. In this talk I will present recent developments at JILA on observing spin-exchange interactions between ultra-long-lived optical dipoles mediated by photons in an undriven optical cavity. The effective spins are encoded in the ground and excited state of the millihertz linewidth strontium clock transition, currently the basis of the most precise atomic clocks. The exchange interactions manifest in our system as a collective XX-Heisenberg spin model, an iconic model that describes the behavior of a broad class of phenomena ranging from superconductivity to quantum magnetism. We observe evidence of two of the main characteristic features of the collective XX- Heisenberg model dynamics an orientation-dependent global spin precession of the collective Bloch vector, referred to as one-axis twisting and the emergence of a many-body energy gap between states of different symmetry. These effects manifest in the output of a pulsed, superradiant laser operating on the millihertz linewidth transition. Our observations will aid in the future design of versatile quantum simulators that take advantage of the unique control and probing capabilities of cavity QED and the rich internal structure of long-lived Sr atoms. They also open a route for the next generation of atomic clocks that utilize quantum correlations for enhanced metrology.

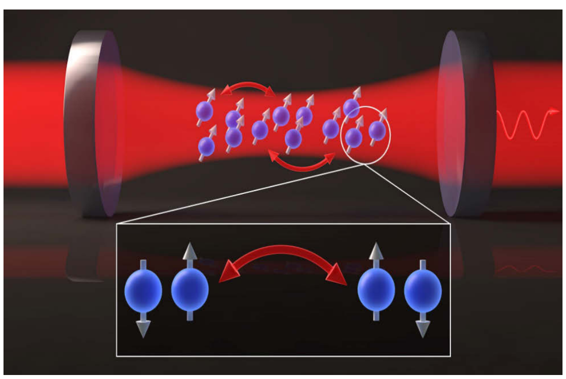

Figure 1. The cavity mode mediates spin-exchange interactions in which one atom emits a photon into the cavity that is then absorbed by another atom, driving spin flips.

Acknowledgements
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Light-induced Azimuthal Gauge Potentials and Spin-orbital-angular-momentum coupling in Bose-Einstein condensates

P.-K. Chen[1], L.-R. Liu[1], N.-C. Chiu[1], H.-R. Chen[1], K.-Y. Lin[1], M.-J. Tsai[1], S.-K. Yip[1,2], Y. Kawaguchi[3], M.-S. Chang[1], Y.-J. Lin[1]

[1]**Institute of Atomic and Molecular Sciences, Academia Sinica,**
Taipei 10617, Taiwan
[2]**Institute of Physics, Academia Sinica,**
Taipei 11529, Taiwan
[3]**Department of Applied Physics, Nagoya University,**
Nagoya 464-8603, Japan

We demonstrate coupling between the atomic spin and orbital-angular-momentum (OAM) of the atom's center-of-mass motion in a Bose-Einstein condensate (BEC), referred to as "spin-orbital-angular-momentum coupling" [1]. This is achieved by using two co-propagating Raman-dressing beams to couple the atoms in the hyperfine spin F=1 manifold while transferring orbital-angular-momentum (OAM) to the atoms' center-of-mass. One of the Raman beam is a Laguerre-Gaussian (LG) beam carrying OAM of light. In this system, we create synthetic azimuthal gauge potentials which act as effective rotations. We exploit the azimuthal gauge potential to demonstrate the Hess-Fairbank effect [2], the analogue of Meissner effect in superconductors. Here, the BEC in the absolute ground state is a coreless vortex state and transits into a polar-core vortex when the synthetic magnetic flux is tuned to exceed a critical value. Our demonstration serves as a paradigm to create topological excitations by tailoring atom-light interactions. Further, the gauge field in the stationary Hamiltonian opens a path to investigating rotation properties of atomic superfluids under thermal equilibrium.

Acknowledgements

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Tuesday

Posters

Spin thermometry of individual neutral impurities coupled to a Bose-Einstein condensate

Daniel Adam[1], Quentin Bouton[1], Tobias Lausch[1], Daniel Mayer[1], Jens Nettersheim[1], Felix Schmidt[1], Artur Widera[1,2]
[1]Department of Physics and Research Center OPTIMAS
Technische Universität Kaiserslautern, Germany
[2]Graduate School Materials Science in Mainz
Gottlieb-Daimler-Strasse 47, Kaiserslautern, Germany

The measurement of (local) thermodynamic properties of a quantum system is the key for a detailed understanding of thermalization and dynamic in nonequilibrium quantum systems. Temperature, i.e. the distribution of kinetic energy, was measured so far by investigating motional dynamics of the total system or impurities immersed.

Here, we present a novel way of local in-situ thermometry based on the spin dynamic of individual neutral Caesium (Cs) atoms with total spin F=3 in an ultracold gas of Rb atoms with total spin F=1. Elastic collisions thermalize the impurity, reflecting temperature in the kinetic energy distribution of the impurities. For the spin degree of freedom, the competition of endo- and exoergic spin-exchange processes map the temperature onto the quasi-spin population of the impurity. The sensitivity of the thermometer can be adjusted via the external magnetic field changing the Zeeman energy splitting. Moreover, our thermometer is not restricted to probing steady-state populations, but we also infer possible enhancement of sensitivity, if temperature information is obtained from nonequilibrium dynamic of the probe.

Our work thus provides a novel way of performing in-situ thermometry by measuring internal state populations rather than atomic motion.

Optical cycling of cold barium monofluoride molecules enabled by magnetic fields

Ralf Albrecht, Tobias Sixt, Lucas Hofer, Michael Scharwaechter and Tim Langen

5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, University of Stuttgart,
Pfaffenwaldring 57, 70569 Stuttgart, Germany

We report on our progress towards the direct laser cooling and trapping of barium monofluoride molecules.

Laser cooling of molecules had long been considered impossible due to their complex vibrational and rotational level structure. However, beneficial Franck-Condon factors and selection rules allow for optical cycling in many molecular species, including barium monofluoride [1].

In our experiment, molecules are generated through laser ablation of a sintered precursor target inside a cryogenic cell. Subsequently, the initially ~10^4 K hot molecules are precooled to the few Kelvin regime by collisions with a cold buffer gas of helium atoms. The precooled molecules exit the cell through a millimeter-sized aperture and enter a room-temperature high-vacuum region, where they form a cold and intense molecular beam. Combining this beam with magnetic remixing of dark states, we realize a quasi-cycling transition that is suitable for future laser cooling of this heavy diatomic molecule.

Acknowledgements

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Impurity dynamics in bright soliton condensates

Christopher Campbell[1], **Matthew Edmonds**[1], **Thomas Busch**[1]

[1]**OIST Graduate University**
Quantum Systems Unit, Okinawa, Japan

In this work we present results on the scattering and self-trapping properties of single atom impurities with bright soliton condensates[1]. The condensates represent a mean-field potential with which the impurities interact through attractive s-wave scattering.

As a first case we consider a particle which scatters off a bright soliton and calculate the reflection coefficient. It is well known that the bright soliton mean-field potential is identical to a Pöschl-Teller potential, which in turn is known to be reflectionless for certain parameters[2]. However, the interaction with the impurity perturbs the perfect Pöschl-Teller shape and one would expect the property of being reflectionless to be lost. Surprisingly this is not the case (see Fig.1) and we show the appearance of periodic recurrences of reflectionless states as a function of the interaction strength between the condensate and the impurity.

To explore the loss of the property of being reflectionless further, we analyze in a second step the eigenstates of the coupled system using a supersymmetry approach. Without the presence of an impurity the supersymmetric partner potential of the mean-field bright soliton potential is known to be free space, and when coupling the impurity we find a systematic change away from this simple form[3].

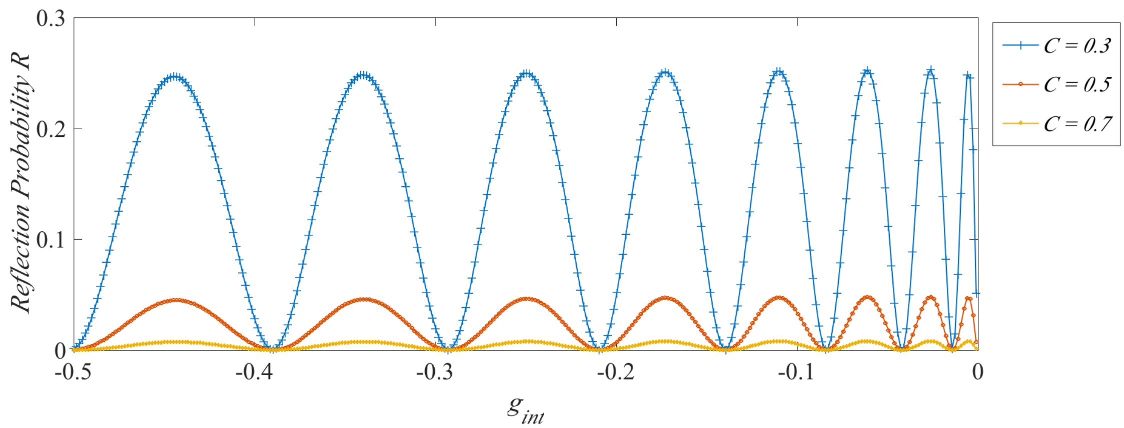

Figure 1. Calculated reflection probability of a particle passing through a bright soliton containing 100 particles with an internal interaction strength of g_{1D} = -.007, as a function of interspecies interaction coupling strengths g_{int}. Velocities are calculated using $v = C\frac{Ng_{1D}}{\hbar}$ where C is an arbitrary constant. Decreasing the velocity and allowing for a longer interaction between the soliton and the particle causes a higher population density to be reflected. As the attractive interactions increase the peaks between reflection less points becomes larger and larger.

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Inter-species entanglement in two-species bosons in optical lattices

Saubhik Sarkar[1,2,3], Suzanne McEndoo[2], Dominik Schneble[4], Andrew J. Daley[2]
[1]Institute of Physics, Polish Academy of Sciences
Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland
[2]Department of Physics and SUPA, University of Strathclyde
Glasgow G4 0NG, UK
[3]Harish-Chandra Research Institute, HBNI
Chhatnag Road, Jhunsi, Allahabad 211 019, India
[4]Department of Physics and Astronomy, Stony Brook University
Stony Brook, New York 11794-3800, USA

The dynamics of impurity atoms introduced into bosonic gases in an optical lattice have generated a lot of recent interest, both in theory and experiment [1]. We investigate to what extent measurements on either the impurity species or the majority species in these systems are affected by their interspecies entanglement, resulting in further reduction in the observation of coherent phenomena [2], beyond what might be expected from an increase in the effective mass of the impurities due to the formation of a polaron [3]. This arises naturally in the dynamics and plays an important role when we measure only one species. We explore the corresponding effects in strongly interacting regimes, using a combination of few-particle analytical calculations and Density Matrix Renormalisation group methods in one dimension. We identify how the resulting effects on impurities can be used to probe the many-body states of the majority species, and separately ask how to enter regimes where this entanglement is small, so that the impurities can be used as probes that do not significantly affect the majority species. The results are accessible in current experiments, and provide important considerations for the measurement of complex systems with using few probe atoms.

Acknowledgements

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Spin Hall effect for microcavity polaritons in the presence of superfluidity

Oleg L. Berman[1], Roman Ya. Kezerashvili[1], Yurii E. Lozovik[2]

[1]New York City College of Technology, City University of New York
300 Jay Street, Brooklyn, NY 11201, USA
[2]Institute of Spectroscopy
Troitsk, Moscow 142190, Russia

The spin Hall effect for polaritons (SHEP) in a transition metal dichalcogenides (TMDC) monolayer embedded in a microcavity is predicted [1]. It is demonstrated that two counterpropagating laser beams incident on a TMDC monolayer can deflect a superfluid polariton flow due to the generation the effective gauge vector and scalar potentials. As shown in Figure 1, two Bragg mirrors placed opposite each other at the antinodes of the confined photonic mode form a microcavity, and a TMDC layer is embedded parallel to the Bragg mirrors within the cavity. The polaritons cloud is formed due to the coupling of excitons created in a TMDC layer and microcavity photons. Two coordinate-dependent, counterpropagating and overlapping laser beams in the plane of the TMDC layer interact with a cloud of polaritons. These laser beams produce the spin-dependent gauge magnetic and electric fields due to strong spin-orbit coupling for electrons and holes in TMDC. It was demonstrated that the polariton flows in the same valley are splitting: the superfluid components of the *A* and *B* polariton flows propagate in opposite directions along the counterpropagating beams, while the normal components of the flows slightly deflect in opposite directions and propagate almost perpendicularly to the beams. We obtained the components of polariton conductivity tensor for polaritons without Bose-Einstein condensation (BEC) and in the presence of BEC and superfluidity. The possible experimental observation of SHEP is discussed.

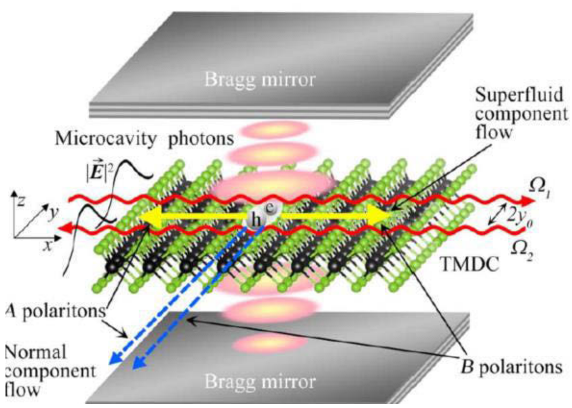

Figure 1. Schematic representation of the SHEP in a TMDC monolayer. The solid and dashed lines with arrows show the directions of deflected superfluid and normal flows of *A* and *B* polaritons, correspondingly. Two counterpropagating laser beams are shown by waved lines.

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Dissipation-Driven Entanglement of Quantum-Dot Polaritons

Matthew Otten[1], Stephen K. Gray[1], and German V. Kolmakov[2]

[1]**Argonne National Laboratory**
9700 S. Cass Avenue, Lemont, IL 60439, USA
[2]**NYC College of Technology, CUNY**
300 Jay Street, Brooklyn, NY 11201, USA

Entanglement of photons is a key part of the recent proposals in quantum simulations, quantum cryptography and quantum communications. Contrary to the conventional wisdom that dissipation destroys quantum coherence, coupling with a dissipative environment can also generate entanglement [1]. We consider a system composed of two quantum dots coupled with a common, damped surface plasmon mode; each quantum dot is also coupled to a separate photonic cavity mode as shown in Figure 1.

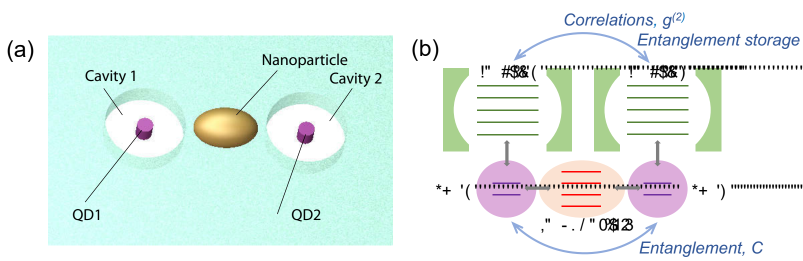

Figure 1. (a) Two quantum dot (QD) are embedded into optical cavities and coupled with plasmonic modes in a neighboring metal nanoparticle. (b) Graphical representation of our model; gray arrows show the respective coupling.

Cavity quantum electrodynamics calculations [2] show that upon optical excitation by a femtosecond laser pulse, entanglement of the quantum dot excitons occurs, and the time evolution of the $g^{(2)}$ pair correlation function of the cavity photons is an indicator of the entanglement. We also show that the degree of entanglement is conserved during the time evolution of the system. Furthermore, the quantum dot entanglement can be transferred to the cavity modes to increase the overall entanglement lifetime. This latter phenomenon can be viewed as a signature of entangled, long-lived QD exciton-polariton formation. The preservation of total entanglement in the strong coupling limit suggests a novel means of entanglement storage and manipulation in high-quality optical cavities.

Acknowledgements

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Tunability of polariton superfluidity in buckled 2D materials by an external electric field

Matthew N. Brunetti[1,2], Oleg L. Berman[1,2], Roman Ya. Kezerashvili[1,2]
[1]New York City College of Technology, City University of New York
300 Jay Street, Brooklyn, NY 11201, USA
[2]The Graduate School and University Center, City University of New York
365 Fifth Avenue, New York , NY 10016, USA

We study the formation of polaritons in the buckled 2D materials – silicene, germanene, and stanene (Xenes) – embedded in an open microcavity under the action of an external electric field perpendicular to the plane of the Xene. The external electric field, together with an open, variable-length optical microcavity, can be used to tune the properties of exciton-polaritons in the Xene. When an electric field is applied to an Xene monolayer, the band gap and the effective masses of electrons and holes increases, which increases the exciton binding energy [1] as well as the Rabi splitting between the upper and lower polariton branches. The length of the microcavity is adjusted independently of the electric field such that the cavity photon mode remains in resonance with the excitonic transition. Furthermore, since the polariton-polariton interaction potential is determined by the binding energy and the Bohr radius of the exciton, the critical temperature of the Berezinskii-Kosterlitz-Thouless (BKT) transition to the superfluid phase is likewise tunable via the electric field. The critical polariton concentrations for the BKT phase transition at T = 300 K are shown in Figure 1. We comprehensively examine the conditions under which lower polaritons may form a stable superfluid at or near room temperature.

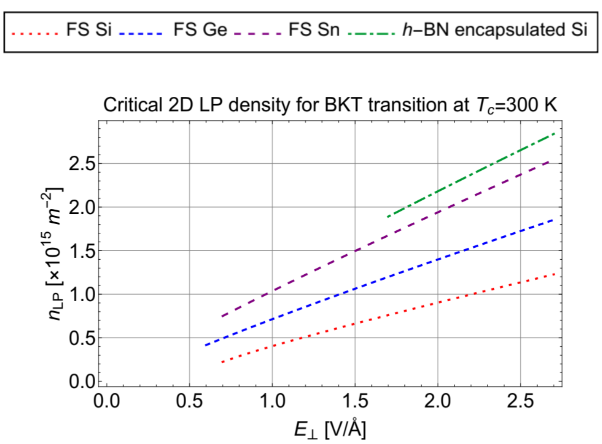

Figure 1. Critical 2D concentration of lower polaritons required for a BKT phase transition at 300 K, as a function of external electric field. The cavity length is chosen to correspond with the excitonic transition energy at a given value of the electric field.

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Translatonary invariant magnetoexciton complexes

V. A. Kuznetsov[1, 2], L. V. Kulik[2], A. S. Zhuravlev[2], A. V. Gorbunov[2], I. V. Kukushkin[1, 2]
[1]National Research University Higher School of Economics
20 Myasnitskaya Street, Moscow, Russia
[2]Institute of Solid State Physics
2 Academician Ossipyan Street, Chernogolovka, Russia

Excitons are unstable in metals, such as 2D-electron gas. Nevertheless, there is a possibility of formation long-living excitons (magnetoexcitons) in a Hall insulator. Magnetoexcitons combine properties of excitons in 2D insulators and plasmons in 2D metals. The simplest realizations are magnetoexcitons formed by an electron promoted from the occupied zeroth Landau level to the empty first Landau level and by the vacancy left in the Fermi sea of electrons. There are two magnetoexcitons: a spin singlet with total spin $S = 0$; and a spin triplet with total spin $S = 1$ and spin projections along the magnetic field axis $S_z = -1, 0, 1$. The singlet magnetoexciton $S = 0$ is the Kohn magnetoplasmon. Its fast relaxation to the ground state occurs via dipole cyclotron radiation. In contrast to the spin singlet, the spin-triplet magnetoexciton is not radiatively active owing to electron spin conservation. The many-body Coulomb interaction lowers its energy below the cyclotron energy. Thus, the spin-triplet magnetoexciton is the lowest energy excited state in the system [1]. Because of this and the spin conservation, the spin-triplet magnetoexcitons exhibit extremely slow relaxation with the relaxation time reaching hundreds of microseconds [2].

Huge lifetime of magnetoexcitons modifies photoluminescence spectrum significantly due to the formation of three particle complexes. We discovered new features in the PL spectrum of the 2D insulator which are clearly attributed to plasmarons (three particle state consisting of a magnetoplasmon and a bound to it extra hole) and plasmon-exciton molecules (an exotic four-particle state consisting of a magnetoplasmon and a bound to it spin-triplet magnetoexciton) [3]. Surprisingly, this PL features give us hint on a momentum value of a single exciton in exciton condensate. [4]

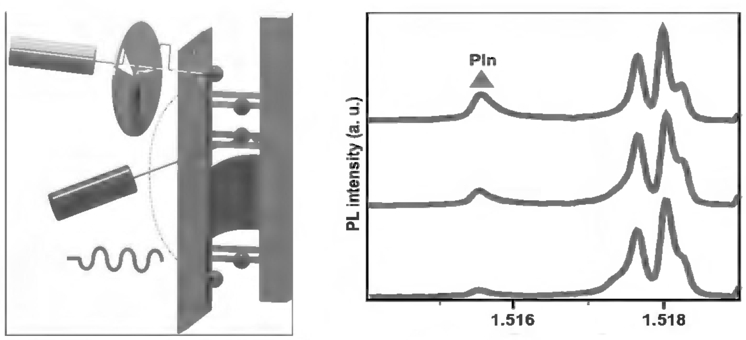

Fig. 1. (a) Experimental setup for creating spin-triplet magnetoexcitons;
(b) Photoluminescence spectra measured at different pumping powers in 2D Hall insulator .

Acknowledgements
This work has been sponsored by the Basic research program of HSE. L. V. K. thanks the Russian Fund for Fundamental Research.

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Drag Effect of a Polariton Condensate in a Quantum Wire

D. M. Myers,[1] B. Ozden,[2] J. Beaumariage,[1] M. Steger,[3]
L. N. Pfeiffer,[4] K. West,[4] and D. W. Snoke[1]

[1]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
[2]Department of Physics and Engineering, Penn State Abington, Abington, PA 19001, USA
[3]National Renewable Energy Lab, Golden, CO 80401, USA
[4]Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA

Polaritons can interact directly with electrons via Coulombic interaction of their exciton component. We can measured the momentum distribution of a polariton condensate when an electrical current is running collinearly with the condensate in a quasi-1D wire. We find that the momentum of the electrons is imparted to the condensate, as seen in the angle of emission of the photons emitted from the system. Since the whole system consists of photons in/photons out, this is effectively a direct transfer of momentum from electrons to photons, via the mechanism shown in Figure 1c, below.

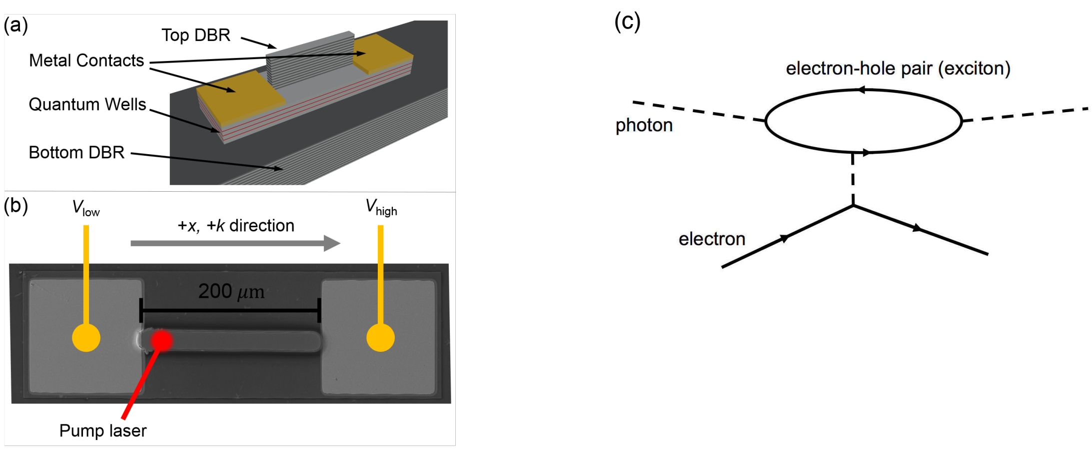

Figure 1. a) Geometry of the experiment allowing optical monitoring of a polariton condensate with collinear free electron propagation. b) The fabricated structure. c) Feynman diagram for the effective photon-electron collision mechanism.

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Locking of Multiple Polariton Condensates at High Density

D. M. Myers,[1] J.K. Wuenschell,[2] B. Ozden,[3] J. Beaumariage,[1]
L. N. Pfeiffer,[4] K. West,[4] and D. W. Snoke[1]

[1]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
[2] National Energy Technology Laboratory (NETL), Pittsburgh, USA
[3]Department of Physics and Engineering, Penn State Abington, Abington, PA 19001, USA
[4]Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA

We have made structures with multiple traps for polariton condensates. A single pump source is used, which feeds four traps. At low powers, separate condensates appear in the traps which have different ground state energies. At higher power, the mean-field repulsive interaction of the particles leads to an expansion of the condensates and an energy shift to higher energy. At a critical threshold, the different condensates lock to the same, global energy state. When this happens, we see a jump in the condensate density as the increased occupation number leads to a faster transition rate of particles from the pump into the condensate, due to stimulated scattering.

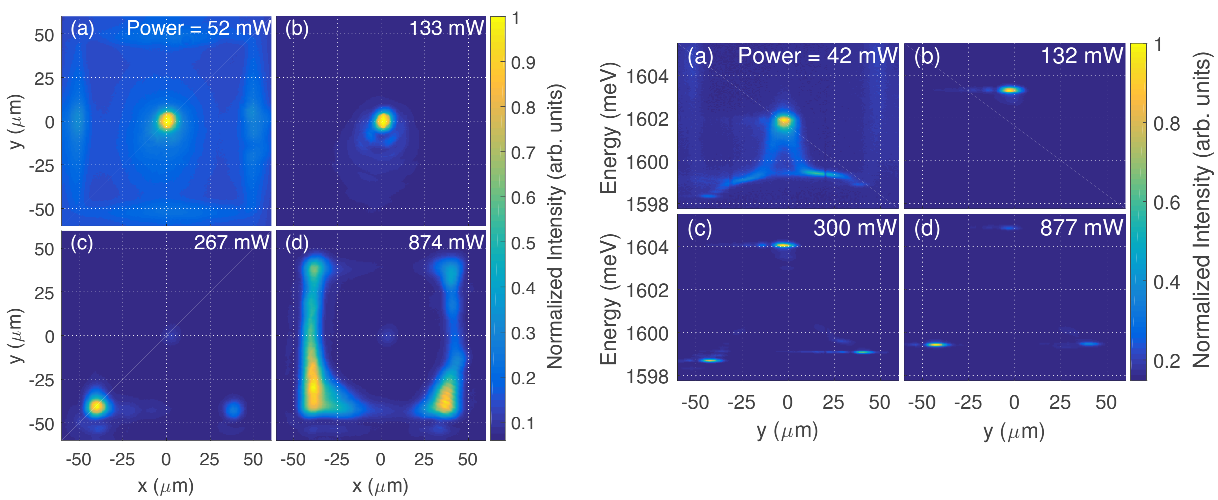

Figure 1. Left: Spatial images, and Right: energy-resolved spatial profile of the polaritons at various densities. (a) Below the condensation density threshold (no condensate). (b) Quasi-condensate at the pump spot at higher density. c) Spatially separated condensates at higher density. d) Global, single condensate at high density.

Acknowledgements: Army Research Office (W911NF-15-1-0466). The work of sample fabrication at Princeton was funded by the Gordon and Betty Moore Foundation (GBMF-4420) and by the National Science Foundation MRSEC program through the Princeton Center for Complex Materials (DMR-0819860).

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Exciton-polariton condensation in the single-shot and Thomas-Fermi regime

E. Estrecho[1,*], T. Gao[1], N. Bobrovska[2], M. D. Fraser[3], M. Steger[4], L. Preiffer[5], K. West[5], T. C. H. Liew[6], M. Matuszewski[2], D. W. Snoke[4], A. G. Truscott[7], & E. A. Ostrovskaya[1]

[1]**Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University,** Canberra, ACT 2601, Australia
[2]**Institute of Physics, Polish Academy of Sciences,** A. Lotników 32/46, 02-668 Warsaw, Poland
[3]**Quantum Functional System Research Group, RIKEN Center for Emergent Matter Science,** 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
[4]**Department of Physics and Astronomy, University of Pittsburgh,** PA 15260, USA
[5]**Department of Electrical Engineering, Princeton University,** New Jersey 08544, USA
[6]**Division of Physics and Applied Physics, Nanyang Technological University,** Singapore
[7]**Laser Physics Centre, Research School of Physics and Engineering, The Australian National University,** Canberra, ACT 2601, Australia

Condensates of exciton-polaritons coexist with an incoherent excitonic reservoir, which serves as the gain medium and a repulsive potential for exciton-polaritons, hence directly affecting the formation, coherence, and dynamics of the condensate. By imaging single realizations of the condensation process [1], we uncover the interplay between the reservoir-condensate interaction and the energy relaxation. The highly nonequilibrium photon-like condensates are essentially multi-mode and display spatial filamentation arising from reservoir depletion, which leads to strong shot-to-shot fluctuations. In contrast, the efficient energy relaxation in exciton-like condensates suppressed these effects and results in a spatially homogeneous, non-fluctuating condensate. Furthermore, by using an optically-induced trap, we successfully create a single-mode, uniform, high-density condensate in the Thomas-Fermi regime that is spatially separated from the reservoir [2]. This regime allows us to draw a clear distinction between the effects of polariton-reservoir and polariton-polariton interaction and enables a reliable measurement of the polariton-polariton interaction strength. The Thomas-Fermi regime opens an opportunity for studies of the condensate properties without the influence of the reservoir, e.g. excitation spectra, collective oscillations, and quantum depletion.

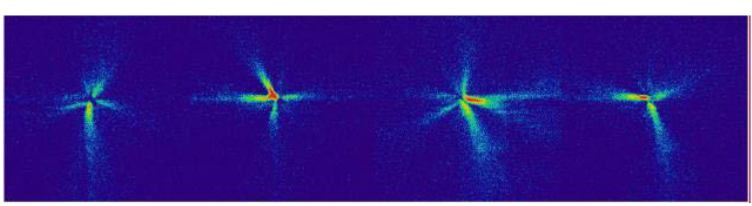

Figure 1. Single-shot images of highly nonequilibrium exciton-polariton condensates [1].

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Evolution from a polariton-BEC to photon laser: Non-Hermitian phase transition and crossover phenomena around the exceptional point

Ryo Hanai[1,2], Alexander Edelman[1], Yoji, Ohashi[3], Peter B. Littlewood[1,4]

[1]**James Frank Institute, University of Chicago**
929 E 57th Street, Chicago, IL, United States of America
[2]**Department of Physics, Osaka University**
1-1 Machikaneyama, Toyonaka, Osaka, Japan
[3]**Department of Physics, Keio University**
3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa, Japan
[4]**Materials Science Division, Argonne National Laboratory**
9700 S. Cass Avenue, Argonne, IL, United States of America

We propose a novel mechanism for a nonequilibrium phase transition within a U(1)-broken phase, from a polariton-BEC to a photon laser, induced by the non-Hermitian nature of a polariton condensate[1]. Starting from an exact equation of motion of a model driven-dissipative electron-hole-photon gas, we show that a (uniform) steady state solution can always be classified into two types, namely, the lower and upper branch condensates. We prove that, an exceptional point, where the two solution types coalesce, marks the endpoint of the first-order-like phase boundary, analogously to a critical point in a liquid-gas phase diagram (See Fig. 1). Our theory provides a possible new interpretation to the second threshold observed in experiments[2] as a lower-to-upper-branch condensate transition. Although our calculation mainly aims to clarify polariton physics, our discussion should be applicable to general driven-dissipative condensates composed of two complex fields.

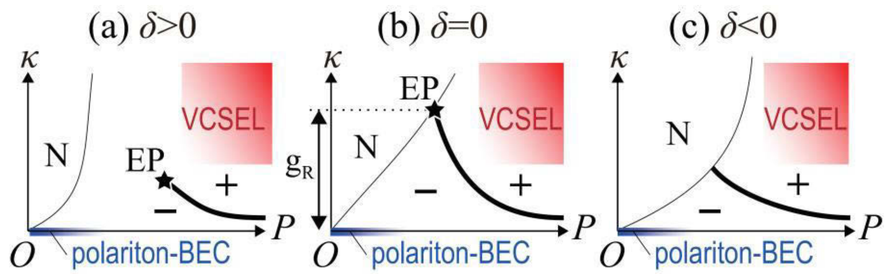

Figure 1. Proposed phase diagram of a driven-dissipative electron-hole-photon gas, in terms the photon decay rate κ and the pump power P at different detuning δ. "$-(+)$" represents the "$-(+)$"-solution phase, "N" represents the normal phase, "EP" is the exceptional point. The thick solid line represents the phase boundary within the condensed phase.

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One-Dimensional Nature of Superconductivity at the $LaAlO_3/SrTiO_3$ Interface

Yun-Yi Pai[1,2], Hyungwoo Lee[3], Jung-Woo Lee[3], Anil Annadi[1,2], Guanglei Cheng[1,2], Shicheng Lu[1,2], Michelle Tomczyk[1,2], Mengchen Huang[1,2], Chang-Beom Eom[3], Patrick Irvin[1,2], Jeremy Levy[1,2]

[1]Department of Physics and Astronomy, University of Pittsburgh
Pittsburgh, PA 15260, USA
[2]Pittsburgh Quantum Institute
Pittsburgh, PA, 15260 USA
[3]University of Department of Materials Science and Engineering, University of Wisconsin-Madison, Madison
WI 53706, USA

We examine superconductivity in $LaAlO_3/SrTiO_3$ channels with widths that transition from the 1D to 2D regime. The superconducting critical current is independent of the channel width and increases approximately linearly with the number of parallel channels. Signatures of electron pairing outside of the superconducting regime are also found to be independent of channel width. Collectively, these results indicate that superconductivity exists at the boundary of these channels and is absent within the interior region of the channels. The intrinsic 1D nature of superconductivity at the $LaAlO_3/SrTiO_3$ interface imposes strong physical constraints on possible electron pairing mechanisms.

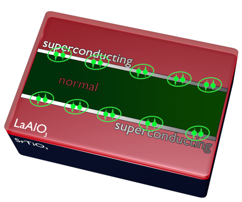

Fig. 1: The results indicate that the superconductivity exists only at the edges of a channel of $LaAlO_3/SrTiO_3$ while the bulk remains in the normal state.

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Uniaxial strain effect on superconductivity in $LaAlO_3/SrTiO_3$ nanostructures

Xinyi Wu[1,2], Megan Briggeman[1,2], Joe Albro[1,2], Jianan Li[1,2], Jungwoo Lee[3], Hyungwoo Lee[3], Chang-Boem Eom[3], Patrick Irvin[1,2], Jeremy Levy[3]

[1]Department of Physics and Astronomy, University of Pittsburgh
Pittsburgh, PA 15260, USA
[2]Pittsburgh Quantum Institute
Pittsburgh, PA 15260, USA
[3]Department of Materials Science and Engineering, University of Wisconsin-Madison
Madison, WI 53706, USA

We investigate the effects of uniaxial strain on superconductivity in nanowires created at the $LaAlO_3/SrTiO_3$ interface using conductive atomic force microscope (c-AFM) lithography. Recently theory predicted a linear dependence of the critical temperature of $SrTiO_3$ on uniaxial and biaxial strain. Our initial experiments indicate that tensile and compressive strains affects the superconducting state at milli-kelvin temperatures. We are exploring the effects of applying continuously tunable strain along different directions relative to the superconducting nanowire. c-AFM written areas are z elongated which seeds z-domains under tetragonal antiferrodistortive transition. Uniaxial strain may move the ferroelastic domain boundaries where it is suggested that superconductivity happens. From uniaxial strain dependence observations, we discuss implications for understanding the electron pairing mechanism in the 2DEG system.

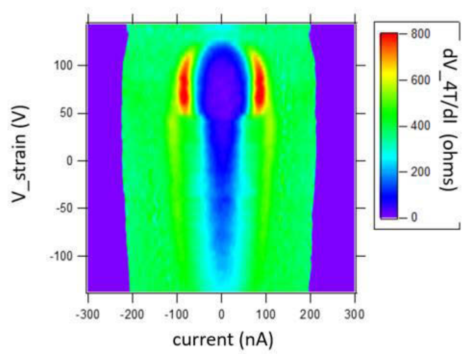

Figure 1. Four terminal conductance data for a nanowire device as a function of applied strain at milli-kelvin temperatures. Superconductivity is indicated by purple region with red on two sides; the figure shows strain-induced superconducting transition.

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Chiral to helical Majorana fermion transition in a *p*-wave superconductor

Haiping Hu[1,2], Indubala I. Satija[1], Erhai Zhao[1]

[1]Department of Physics and Astronomy,
George Mason University, Fairfax, Virginia 22030, USA
[2]Department of Physics and Astronomy,
University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA

Chiral and helical Majorana edge modes are two archetypal gapless excitations of two-dimensional topological superconductors. They belong to superconductors from two different Altland-Zirnbauer symmetry classes characterized by Z and Z_2 topological invariant respectively. It seems improbable to tune a pair of co-propagating chiral edge modes to counter-propagate without symmetry breaking. Here we show that such a direct topological transition is in fact possible, provided the system possesses an additional symmetry O which changes the bulk topological invariant to $Z\oplus Z$ type. A simple model describing the proximity structure of a Chern insulator and a p_x-wave superconductor is proposed and solved analytically to illustrate the transition between two topologically nontrivial phases [Figure 1]. The weak pairing phase has two chiral Majorana edge modes, while the strong pairing phase is characterized by O-graded Chern number and hosts a pair of counter-propagating Majorana fermions. The bulk topological invariants and edge theory are worked out in detail. Implications of these results to topological quantum computing based on Majorana fermions are discussed.

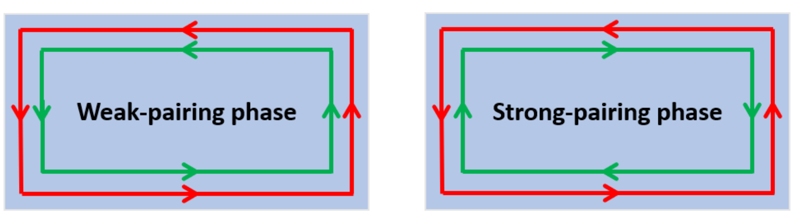

Figure 1. Illustration of chiral (left) and helical (right) Majorana edge modes in the weak- and strong-pairing superconductors.

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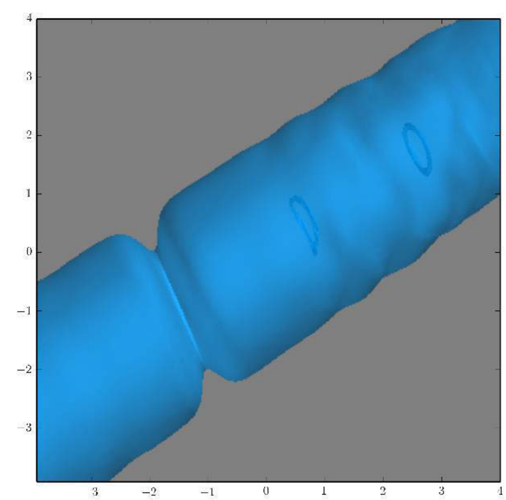
Vortex-Induced Dissipation Across a Josephson Junction

K Xhani[1,2], E Neri[2,3], M Zaccanti[2,3], KL Lee[1], L Galantucci[1], A Trombettoni[4], F Scazza[2,3], A Burchianti[2,3], G Roati[2,3] and NP Proukakis[1]

[1]Joint Quantum Centre (JQC) Durham-Newcastle, Newcastle University, UK
[2]LENS and Dipartimento di Fisica e Astronomia, Universita di Firenze, Florence, Italy
[3]Istituto Nazionale di Ottica del Consiglio Nazionale Ricerche (CNR-INO), Florence, Italy
[4]Istituto Officina dei Materiali del CNR, Trieste, Italy

The dynamics across a Josephson junction is known to exhibit two types of behavior, depending on the relative population imbalance across the junction, namely Josephson oscillations (small imbalance) and macroscopic self-trapping (large imbalance). Recent experiments observed the transition from Josephson oscillations to a dissipative regime, through the generation of vortices in the region of the barrier coupling two parts of a superfluid from the BEC to the BCS limit [1,2]. We explain this process quantitatively, and study the emerging Josephson junction phase diagram, by performing detailed numerical simulations at both T = 0 and T > 0 in the molecular BEC regime [3].

The onset of the dissipative regime strongly depends on the barrier height, V_0, and is characterised in terms of the critical initial population imbalance, z, between the two wells and the maximum superfluid current. We show that the defects generated inside the barrier are vortex rings (see image) that can enter eventually in the bulk, depending on barrier height, and give a full characterisation of the emerging vortex ring dynamics (including position, radius, and shape oscillations). In particular we show the dependence of the first vortex ring nucleation time, velocity and lifetime on the value of the initial population imbalance.



Experimentally the vortex rings are observed in time of flight (TOF) images after gradually removing the barrier. We consider this effect and show that the barrier removal process strongly enhances the vortex ring stability, thus facilitating its experimental observation, even in the presence of a small non-condensed (thermal) fraction.

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Far-from-equilibrium dynamics of molecules in ^{4}He nanodroplets: a quasiparticle perspective

G. Bighin[1], **I.N. Cherepanov**[1], **R. Schmidt**[2], **M. Lemeshko**[1]

[1]**IST Austria (Institute of Science and Technology Austria)**
Am Campus 1, 3400, Klosterneuburg, Austria
[2]**Max Planck Institute of Quantum Optics**
Hans-Kopfermann-Str. 1, 85748 Garching, Germany

Angular momentum plays a central role in a plethora of quantum processes, from nuclear collisions to decoherence in quantum dots to ultrafast magnetic switching. Here we consider a single molecule embedded in a superfluid Helium nanodroplet as a prototype of a fully controllable many-body system in which to reveal angular momentum dynamics: an ultrashort, high-intensity laser pulse can induce molecular axis alignment, creating extreme out-of-equilibrium conditions, while imaging of molecular fragments after Coulomb explosion allows to obtain time-resolved measurements of molecular alignment [1].

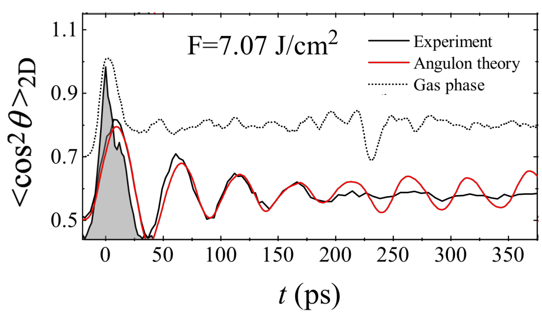

Figure 1. Molecular alignment of an I_2 molecule in superfluid Helium as a function of time: theory (red) vs. experiment (black).

The rotational dynamics of a molecule in superfluid Helium cannot be simply understood in terms of interference of rotational molecular states due to the strong interactions with many-body environment: we show that this scenario can be described in terms of the angulon quasiparticle [2,3] – a quantum rotor dressed by a field of many-body excitations – with a very good agreement with experimental data [4] for several molecular species and across a wide range of laser fluences. The dynamical theory we develop contributes to advancing the understanding of angular momentum dynamics in a many-body environment, with applications ranging from ultracold molecules to condensed matter.

Acknowledgements

This work has been supported by the Austrian Science Fund (FWF), project Nr. P29902-N27 and Nr. M2461-N27.

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Thermodynamics of bosons in the lowest Landau level

Bhilahari Jeevanesan[1] and Sergej Moroz[1]

[1] *Department of Physics, Technical University of Munich, 85748 Garching, Germany*

We make a study of superfluids, by starting with the microscopic Hamiltonian of weakly-interacting Bosons that rotate inside a confining trap. We focus on the limit of large rotation frequencies, which permits us to study the system in the lowest Landau level (LLL). The partition function, expressed as a functional integral, becomes particularly simple in the LLL subspace. Every contribution to the path integral is a linear combination of LLL orbitals and the zeros of such a linear combination are the center positions of vortices in the superfluid. At low temperatures these vortices arrange themselves into the well-known vortex lattice, which melts into a vortex liquid with increasing temperature. We focus on studying the thermodynamics of this interacting system of bosons.

The partition function for this problem can be formulated in such a way that the thermodynamics becomes encoded into a function Φ of a single combination of temperature, chemical potential and interaction strength. After recasting the thermodynamics in terms of Φ, we use Monte Carlo simulations to determine this function numerically. Furthermore, we find a new controlled expansion around $\mu = 0$, which allows us to derive asymptotic formulas for Φ and many other thermodynamic quantities. This analytical approach gives us results that are in good agreement with the numerics.

Wednesday

Talks

Mass Transport through dislocation network in solid ^{4}He

Jaeho Shin, Moses H. W. Chan

Department of Physics, The Pennsylvania State University,
University Park, Pennsylvania 16802-6300, USA

We studied the transport of ^{4}He atoms through 2.5 mm thick solid ^{4}He samples sandwiched between two superfluid leads with five different tailored made sample cells. Measurements in a cell with a barrier at the center of the solid samples and in a cell filled with silica aerogel establish the causal relation between the observed mass flow and the dislocation network in the solid sample. Comparing the results from these cells and prior measurements on solid samples with thicknesses of 2 cm [1,2] and 8 μm [3] reveals that the mass flow rate decreases logarithmically with the thickness of the solid ^{4}He. Interestingly the mass flow exhibit both superfluid and Bosonic Luttinger liquid characteristics at low temperature (see Figure. 1).

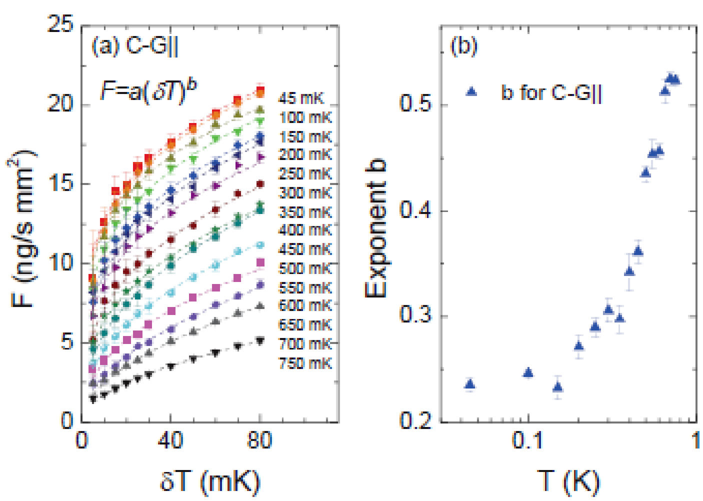

Figure 1. (a) Mass flow rate of solid ^{4}He as a function of thermal bias, δT, at different temperature. The dashed lines show the simple power-law fitting, $F = a(\delta T)^b$. (b) Exponent b is found to be 0.24 for T < 150 mK, and increases with sample temperature.

Acknowledgements

This research is supported by NSF under grant DMR-1707340.

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Coherent Optical Manipulation of Single Electrons in Superfluid Helium-4

Matthew Otten[1], Xianjing Zhou[1], Dafei Jin[1]

[1]**Argonne National Laboratory**
9700 S Cass Ave, Argonne, USA

An electron in superfluid helium-4 forms a self-trapped cavity called electron bubble. Each bubble contains a single-electron wavefunction, which can undergo optical transitions from its 1S ground state to 1P excited state. Previous studies on the optical manipulation of electron bubbles mainly focused on incoherent pumping by a weak continuous light source. Here we theoretically demonstrate that a commercial femtosecond laser with 100-200 fs pulse duration and microJoule pulse energy is powerful enough to induce the coherent Rabi oscillations of the electron between 1S and 1P states. By controlling the laser power and thus the Rabi period, the electron can be pulse-gated onto an arbitrary superposition of 1S and 1P states. The end state can cause a deformation of superfluid helium towards a metastable bubble shape with exceedingly long lifetime of the order of microseconds. The electron-bubble system can be an ideal platform for storing quantum optical information and exhibiting unique properties of an open quantum system.

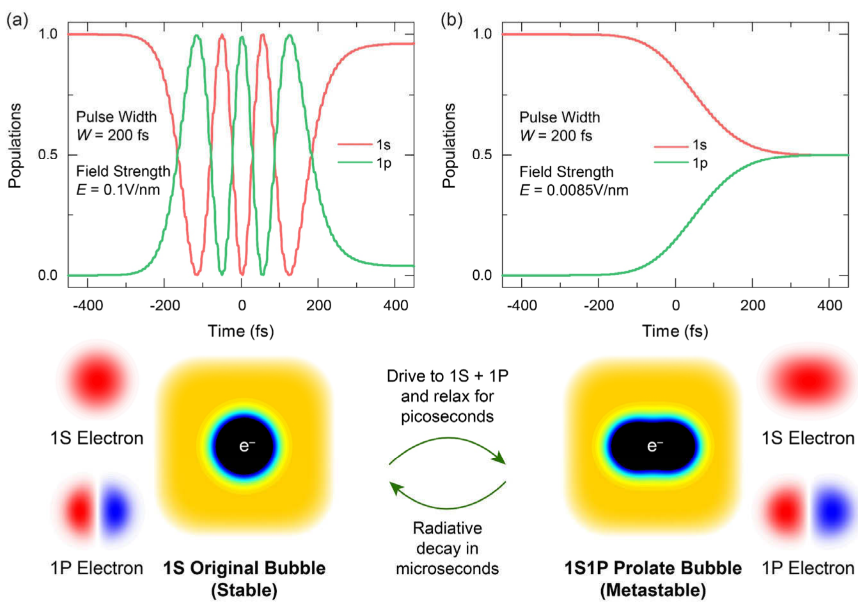

Figure 1: Coherent optical manipulation of a single electron in superfluid He-4. (a) The electron undergoes several Rabi cycles and drops back to the 1S ground state. (b) The electron ends up at an equal superposition of the 1S and 1P state with the bubble shape deformed into a prolate spheroid. This state is metastable and can have microsecond lifetime until the electron radiative decay back to the original 1S ground state.

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Superconductor-Insulator Transition and Fermi-Bose Crossovers

Nandii Trivedi*

The Ohio State University
Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA

The direct transition from an insulator to a superconductor (SC) in Fermi systems is a problem of long-standing interest, which necessarily goes beyond the standard BCS paradigm of superconductivity as a Fermi surface instability. We introduce here a simple, translationally invariant lattice fermion model that undergoes a SC-insulator transition (SIT) and elucidate its properties using analytical methods and quantum Monte Carlo simulations. We show that there is a fermionic band insulator to bosonic insulator crossover in the insulating phase and a BCS-to-BEC crossover in the SC. The SIT is always found to be from a bosonic insulator to a BEC-like SC, with an energy gap for fermions that remains finite across the SIT. The energy scales that go critical at the SIT are the gap to pair excitations in the insulator and the superfluid stiffness in the SC [1]. In addition to giving insight into important questions about the SIT in solid-state systems, our model should be experimentally realizable using ultracold fermions in optical lattices. We will also discuss the best parameter regimes in model systems to observe quantum phase transitions from trivial and topological insulators to topological superconductors [2].

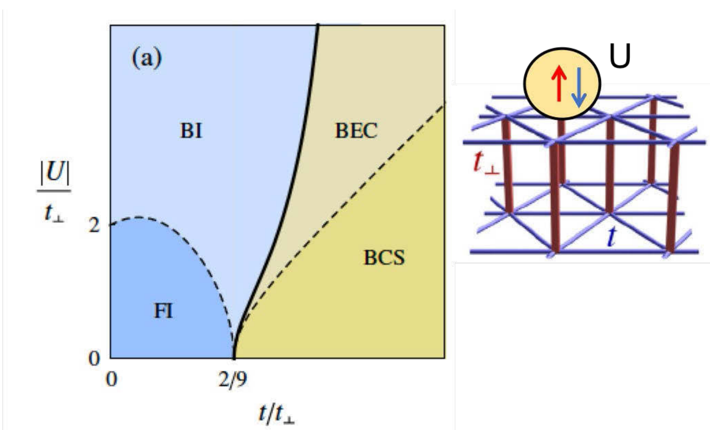

Figure 1. Quantum phase transition from a Fermi band insulator (FI) to a BCS superconductor via two intervening bosonic crossovers: from a Fermi to Bose insulator (BI), and, BEC to BCS crossover. Specific results shown for a triangular bilayer with hopping *t* within and $t_\perp$ between layers and U is the onsite attraction.

* In collaboration with Yen Lee Loh, Tamaghna Hazra, Chia-Chen Chang, Richard Scalettar and Mohit Randeria

Acknowledgements
This work has been sponsored by DOE-BES grant DE-FG02-07ER46423

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A monolayer transition metal dichalcogenide as a topological excitonic insulator

Daniele Varsano[1], Maurizia Palummo[2], Elisa Molinari[1,3], Massimo Rontani[1]

[1]CNR-NANO
Via Campi 213a, 41125 Modena, Italy
[2]Dipartimento di Fisica, Università degli Studi di Roma Tor Vergata
Via della Ricerca Scientifica 1, 00133 Roma, Italy
[3]FIM, Università degli Studi di Modena e Reggio Emilia
Via Campi 213a, 41125 Modena, Italy

Monolayer transition metal dichalcogenides in the T' phase promise to realize the quantum spin Hall effect [1] at room temperature, because they exhibit a prominent spin-orbit gap between inverted bands in the bulk [2,3], as illustrated in Fig. 1(a). Here we show that the binding energy of electron-hole pairs excited through this gap is larger than the gap itself in a paradigmatic material, MoS_2, on the basis of many-body perturbation theory from first principles [4]. This paradox hints at the instability of the T' phase against the spontaneous generation of excitons [Fig. 1(b)], leading to a recostructed ‘excitonic insulator’ ground state [5], as shown by a self-consistent calculation. In contrast to other systems in which topological and excitonic orders are thought to compete, like InAs/GaSb and HgTe/CdTe bilayers [6,7], we predict that here the two orders coexist by breaking the crystal inversion symmetry. This excitonic topological insulator departs distinctively from the bare topological phase: spontaneous electric polarization appears below the Curie temperature of 700 K, Kramers-degenerate bands split, and the bulk gap increases, additionally protecting edge states.

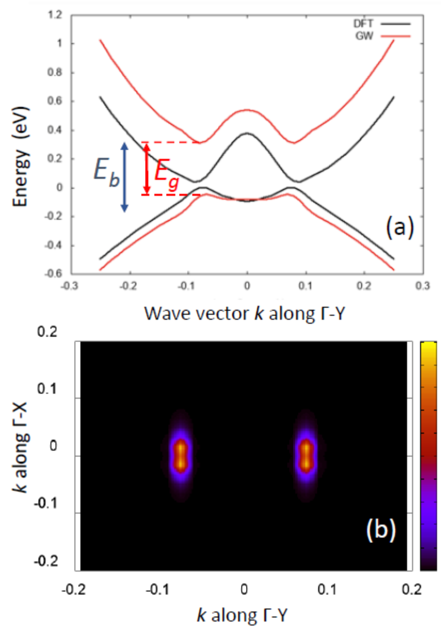

Figure 1. Band structure and excitons of monolayer T'-MoS_2 from first principles. (a) Band structure along the ΓY direction in **k** space. Black and red curves are DFT and GW predictions, respectively. (b) Square modulus of exciton wave function in **k** space. The exciton binding energy obtained from the Bethe-Salpeter equation, E_b, exceeds the GW gap, E_g, so the system is unstable against exciton condensation.

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Floquet Higher-Order Topological Insulators: Topology and Comprehensive Detection in Optical Lattices

Biao Huang[1], **W. Vincent Liu**[1,2,3]

[1]**Department of Physics and Astronomy, University of Pittsburgh**
Pittsburgh PA 15213, USA
[2]**Wilczek Quantum Center, Shanghai Jiao Tong University**
Shanghai 200240, China
[3]**Southern University of Science and Technology,**
Shenzhen 518055, China

The theoretical and experimental discovery of topological insulators of higher multipole nature, dubbed "higher order topological insulators" (HOTI), has triggered heated discussions in recent studies. But so far, all researches have been limited to static systems due to the lack of higher order topological invariants constructed for a genuine dynamical system. Here, we report a highly solvable Floquet-driven model showing the anomalous corner states and a construction of dynamical topological invariant built upon evolution operators $U(t)$. Further, a comprehensive scheme to prove not only corner state but also their anomalous nature of dynamical origin is proposed, with the latter one never demonstrated in any previous experiment. Our work paves the way to the systematic study of HOTI in regimes far away from equilibrium.

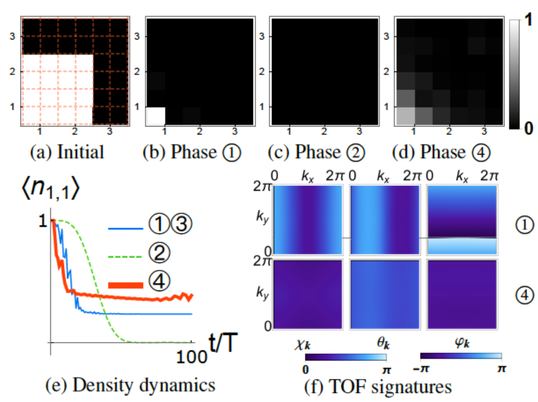

Figure 1. Simulations for experimental detections. The corner particle dynamics in (a)—(e) is accompanied by the Floquet band tomography in (f), showing that the corner mode in anomalous Phase 4 is due to dynamics of $U(t)$ rather than the static trivial Floquet operator U_F.

Acknowledgements

This work is supported by AFOSR Grant No. FA9550-16-1-0006, ARO Grant No. W911NF-11-1-0230, MURI-ARO Grant No. W911NF-17-1-0323 and NSF of China Overseas Scholar Collaborative Program Grant No. 11429402 sponsored by Peking University.

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Disordered bosons: from superfluid to Bose glass in quantum magnetic insulators and cold atomic gases

Thierry Giamarchi, University of Geneva

Abstract:

Disorder has a profound effect on the properties of quantum interacting systems. When interactions are absent this leads to the celebrated Anderson localization. With interactions, and in particular for bosons, there is a fierce competition between the tendency to form superfluid states and the localization, leading to interesting quantum phase transitions between BEC/superfluid states and Bose glass states.

I will discuss how both quantum antiferromagnetic insulators, in a condensed matter context, and alternatively cold atomic gases can be used to tackle some of the issues associated with this very challenging problem.

Bose-Einstein Condensation in Quantum Dimer Systems: Dimensionality, Transport, and Out-of-Equilibrium

Christian Rüegg
Division Research with Neutrons and Muons, Paul Scherrer Institute
Department of Quantum Matter Physics, University of Geneva, Switzerland

Abstract:

Materials made of arrays of quantum spins forming well-defined lattices of dimers serve as model systems to study magnon Bose-Einstein Condensation (BEC). In three-dimensional lattices BEC has now been confirmed experimentally for a large number of materials. For one-dimensional systems spin Luttinger-liquid physics and its transition to the BEC at very low temperatures has been explored in great quantitative detail. More exotic forms of BEC like spin super-solids and Bose glass phases are currently studied experimentally in a growing number of materials.
The focus of my overview presentation will be on three current frontiers. First, I will present the elusive, two-dimensional case and its limitations and transitions to the BEC. Second, I will advertise the combination of tuning parameters and specifically of magnetic field (typically controlling the BEC) and pressure (controlling the spin exchange Hamiltonian) for studies of multi-critical points. Third, I will highlight some perspectives and ideas for future work on transport and other out-of-equilibrium BEC phenomena in dimerized magnetic insulators. In the latter context, I will emphasize recent developments in computational physics and exciting new opportunities that free electron lasers will offer to study the time-dependence and out-of-equilibrium dynamics of magnon BEC systems.

Suppression of the exciton Bose condensate in $TiSe_2Cu_x$ by electron doping

Melinda Rak[1], Samantha Rubeck[1], Matteo Mitrano[1], Ali Husain[1], Anshul Kogar[2], Jasper van Wezel[3], Goran Karapetrov[4], Emilia Morosan[5], Peter Abbamonte[1]

[1]Department of Physics, University of Illinois at Urbana-Champaign
Urbana, IL, 61801, USA
[2]Department of Physics, MIT
Cambridge, MA, 02142, USA
[3]Institute of Physics, University of Amsterdam
1090 GL Amsterdam, The Netherlands
[4]Department of Physics, Drexel University
Philadelphia, PA, 19104, USA
[3]Department of Chemistry, Rice University
Houston, TX, 77005, USA

The transition metal dichalcogenide semimetal 1T-$TiSe_2$ exhibits a Bose condensate of excitons traditionally referred to as an "excitonic insulator" (though the material is not technically insulating) and highlighted as "excitonium" in the popular press. Using momentum-resolved electron energy-loss spectroscopy (M-EELS) experiments with meV energy resolution, we showed the experimental signature of this phase is a soft plasmon whose frequency falls to zero at the Bose condensation temperature [1]. Here, we analyze the stability of this phase against electron doping by performing M-EELS experiments in intercalated $TiSe_2Cu_x$. We find that the excitonic state is quickly suppressed, the soft plasmon effect disappearing for $x > 0.01$ which coincides with the semimetal-metal transition (suitably defined). Surprisingly, we find that the periodic lattice distortion accompanying the excitonic transition persists, evolving into a trivial structural phase transition. Our study shows that exciton condensation is quickly destabilized when the Coulomb interaction is suppressed by metallic screening.

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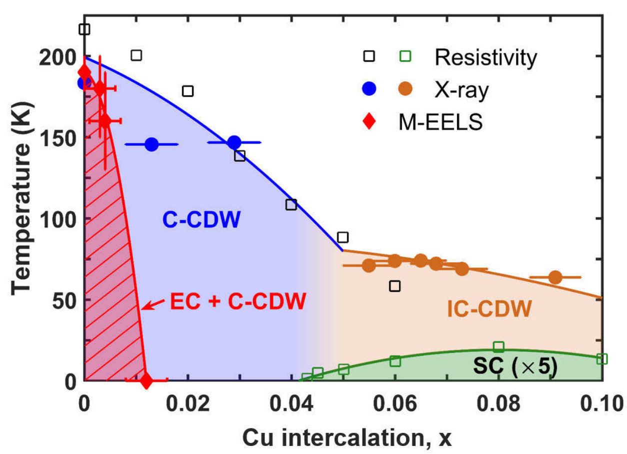
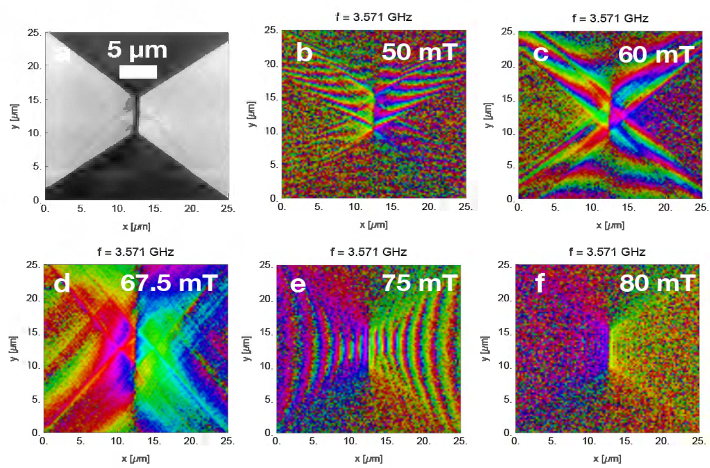


Figure 1 Phase diagram of electron-doped 1T-$TiSe_2Cu_x$. The excitonic transition is quickly suppressed by Cu intercalation, disappearing at the semimetal-to-metal phase transition.

Magnons in ultrathin yttrium iron garnets

Joe Bailey

Magnonics, the study and development of devices utilising collective spin excitations, is a rapidly growing field, covering both fundamental topics (antiferromagnetism[1], quasiparticle condensates[2]) and technological applications (MRAM[3], spintronics[4]). Yttrium iron garnet (YIG) is a ferrimagnetic insulator with the lowest known magnon damping factor of any material [5]. This low damping leads to a prevalence of nonlinear effects and notably the room temperature Bose-Einstein condensation (BEC) of magnons first reported by Demokritov et al in 2006[6], and subject of a number of investigations since [7]-[10]. Ultrathin structures will be required for applications but remain largely unexplored. Here I report on the design, fabrication and characterization of microwave devices based on such ultrathin structures (YIG thickness~100nm). Spin waves were measured using both Brillouin Light Scattering (BLS) and time resolved scanning transmission x-ray microscopy (TR-STXM), locked in phase with microwave stimulation of the devices. A number of milestones are reached for our novel devices. First, we have explicitly measured the spin wave dispersion in YIG[11], and demonstrate the existence of the finite momentum minimum required for magnon BEC. Second, the BLS data demonstrate that the condensate exists in our samples. These results are a key development towards adding condensate phenomena to the thin film magnonics toolbox.



Phase resolved measurement of spin waves in YIG. *Scanning x-ray microscope images are acquired synchronously with a CW RF excitation. The signal (3.5 GHz) is applied to the sample via a transmission line, exciting spin wave modes according to the external field and resulting dispersion. a) shows a transmission snapshot, the dark region is the RF line, the light grey region is the YIG, with the subtle changes in contrast being dynamic magnetic contrast. b)-f) show the amplitude and phase of the dynamics at the excitation frequency extracted via an FFT and mapped onto the brightness and hue channel in a hue saturation brightness (HSB) colour space.*

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Nobel Laureate William Phillips presents:

TIME, EINSTEIN, and the COOLEST STUFF IN THE UNIVERSE.

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7th Floor Auditorium Alumni Hall

This lecture involves
EXCITING LIVE DEMONSTRATIONS
aimed at a general audience of children and adults.

William Phillips is a Fellow of the National Institute for Standards and Technology (NIST) and Distinguished University and College Park Professor of physics at the University of Maryland. In 1997 he was a co-recipient of the Nobel Prize in Physics "for development of methods to cool and trap atoms with laser light." Bill and his collaborators pioneered the technique of laser cooling and trapping atoms. One result of the development of laser-cooling techniques was the first observation, in 1995, of the Bose-Einstein condensate, a new state of matter originally predicted 70 years earlier by Einstein.

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University of Pittsburgh Department of Physics & Astronomy

At the beginning of the 20th century Einstein changed the way we think about Time. Now, a century later, the measurement of Time is being revolutionized. Atomic clocks, the best timekeepers ever made, are one of the scientific and technological wonders of modern life. Such super-accurate clocks are essential to industry, commerce, and science; they are the heart of the Global Positioning System (GPS), which guides cars, airplanes, and hikers to their destinations. Today, the best primary atomic clocks use ultracold atoms, achieve accuracies of about one second in 300 million years.

Super-cold atoms, with temperatures that can be below a billionth of a degree above absolute zero, use, and allow tests of, some of Einstein's strangest predictions.

Thursday

Talks

Ultra-light axion dark matter

Lam Hui, Columbia University

Abstract:

We will discuss the particle physics motivations for the idea that dark matter is comprised of an ultra-light axion. In the ultra-light limit, dark matter is better thought of as waves instead of a collection of particles. Its superfluid nature has many interesting astrophysical implications which we will review.

Dark Matter Superfluidity

Justin Khoury, University of Pennsylvania

Abstract:

This talk will review various recent new proposals about dark matter, beyond the paradigm of Weakly Interacting Massive Particles (WIMPs). These approaches are motivated by the the increasingly stringent bounds from direct detection dark matter experiments and the Large Hadron Collider, which have closed much (but not all) of the WIMP parameter space. They are also motivated by a number of observational puzzles on galactic scales, such as the various empirical scaling relations between baryonic and dark matter distributions, which were not anticipated and are remarkably tight. This talk will discuss, in particular, the recent idea of superfluid dark matter, in which dark matter Bose-Einstein condenses in a superfluid phase in the central regions of galaxies. The superfluid phonons couple to ordinary matter and mediate a new long-range force. For a certain choice of superfluid equation of state, the resulting dynamics naturally explain the observed galactic scaling relations. The model makes various observational predictions that distinguishes it from the standard Lambda-Cold-Dark-Matter model. In the last part of the talk, I will discuss an attempt at explaining cosmic acceleration as yet another manifestation of dark matter superfluidity.

Ultra-light dark matter: a BEC?

Dan Boyanovsky, University of Pittsburgh

Abstract:

Dark Matter may be in the form of an ultra-light scalar degree of freedom. We report on the study of the production of such particle from gravitational expansion, leading to a non-adiabatic production of low momentum pairs in a squeezed state. The physics is similar to parametric amplification and excitation by counter-adiabatic driving in condensed matter systems (here by gravitational expansion), yielding a distribution function of pairs peaked at low momentum.

Entropy from Black Holes to Bose Condensates

Marlan Scully

Texas A&M, Princeton, and Baylor Universities

One often hears that:

1) "The energy and entropy of ground state atoms in a BEC[1] vanish" and

2) "There is no Unruh acceleration from atoms freely falling into a black hole.[2]"

Both of these statements are incorrect and both have an interesting connection with laser physics.

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Friday

Talks

Ultracold atoms as quantum simulators for new materials –optical lattices and synthetic gauge fields

Wolfgang Ketterle, Massachusetts Institute of Technology

Abstract:

When atoms are cooled to nanokelvin temperatures, they can easily be confined and manipulated with laser beams, and new Hamiltonians can be engineered. Crystalline materials are simulated by placing the atoms into an optical lattice, a periodic interference pattern of laser beams. With the help of laser beams, neutral atoms can move around in the same way as charged particles subject to the magnetic Lorentz force. This has been used to realize synthetic magnetic fields and spin-orbit coupling. These and other tools are now applied towards various spin Hamiltonians and topological physics.

From Condensation of Photons to Polaritons in Organic Microcavities

<u>Peter Kirton</u>[1]
[1]**Atominstitut, TU Vienna**
1040, Vienna, Austria

In recent years condensation has been observed in systems which consist of organic molecules trapped in a microcavity. In the weak light-matter coupling limit, dye molecules have been used to observe BEC of photons [1] while in the strong light-matter coupling limit, polariton condensation has been observed at room temperature [2,3]. These experiments pose several questions about the relationship between condensation and lasing, and about the role played by vibrational modes of the molecules. I will discuss our recent work on these subjects.

In the context of photon condensation, I will discuss the role of vibrational modes in establishing a thermal distribution of photons [4]. In the context of polariton condensation I will discuss our work exploring the nature of the ground and excited states of a model of such a system [5]. Finally, I will describe our recent results studying how the crossover between these two limits emerges [6].

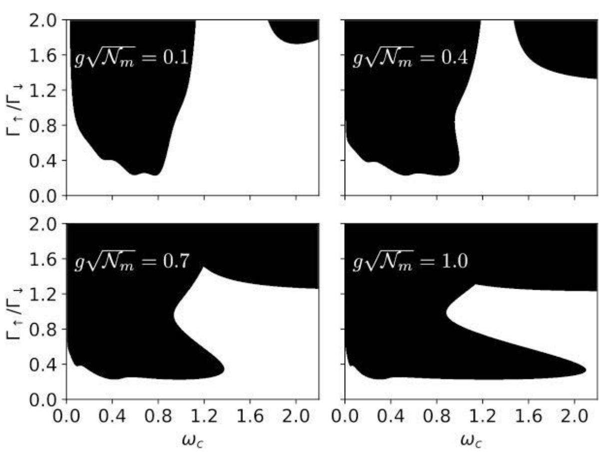

Figure 1. Phase diagram of a model of organic microcavity condensation showing the evolution from weak to strong light-matter coupling.

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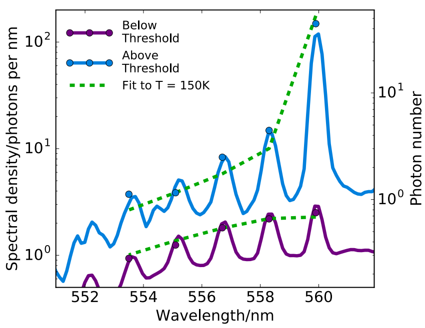
Driven-dissipative non-equilibrium Bose–Einstein condensation of less than ten photons

Benjamin T. Walker[1], Florian Mintert[1], Jason M. Smith[2] and Robert A. Nyman[1]

[1]Imperial College London
Prince Consort Road, London, UK

[2]University of Oxford
Oxford, UK

Bose-Einstein condensation is formally defined only in the thermodynamic limit of infinite-size box, or infinitesimal spacing between energy levels, but this limit is experimentally unobtainable. The Bose-Einstein distribution on the other hand, only assumes an infinite bath with which the system of interest can exchange particles, and so we can use the distribution as the basis for distinguishing condensed from un-condensed Bose gases.



In this work, we use a dye-filled optical microcavity to create a driven-dissipative system of thermalized bosons (here, photons), where the shape of the mirrors define a trapping potential, chosen in this case to give us a 2D harmonic trap, with mode spacing so large that we can monitor the populations of individual energy levels.

We consider that condensed modes have populations which increase linearly with total population, and "depleted" modes' populations saturate at large particle numbers [3]. A suitable threshold for condensation is when the number of photons in the ground state exceeds the square root of the total. We find a condensation threshold with an average of 7 ± 2 photons in the system at any one time – to our knowledge the smallest such condensate in the literature.

We find good agreement between our results and a full master equation simulation of the system, and study the temporal coherence properties of the condensate. We also show experimentally and theoretically that, when the thermalisation is slower than the drive and dissipation, BEC breaks down to give multi-mode condensation which is distinct from the conventional lasing phase transition.

Acknowledgements
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Splitting of Photons by Cooling

Christian Kurtscheid[1], **David Dung**[1], **Erik Busley**[1], **Frank Vewinger**[1], **and Martin Weitz**[1]

[1]**University of Bonn**
Wegelerstr. 8, 53115 Bonn, Germany

Bose-Einstein condensation has been achieved with ultracold atomic gases, exciton-polaritons, and more recently with photons in dye-filled optical microcavities.
We report on the demonstration of a photon Bose-Einstein condensate in the 'bonding' low energy superposition state of a double well potential (Fig. 1). As to provide the correct density of states to allow for Bose-Einstein condensation, the double well potential is superimposed by a shallow harmonic trapping potential. As in earlier works of our group, thermalization of the photon gas (to room temperature) is achieved by absorption and re-emission processes on dye molecules in liquid solution [1]. The described potential for the photon gas is generated by spatial structuring of the surface of one of the cavity mirrors, with a wavelength-sized mirror spacing introducing a low frequency cutoff.
The 'bonding' low energy eigenstate is the system ground state of the cavity photons. The observed Bose-Einstein condensation of photons achieves macroscopic population of this linear combination of the optical wavefunction in the two microsites by cooling alone.

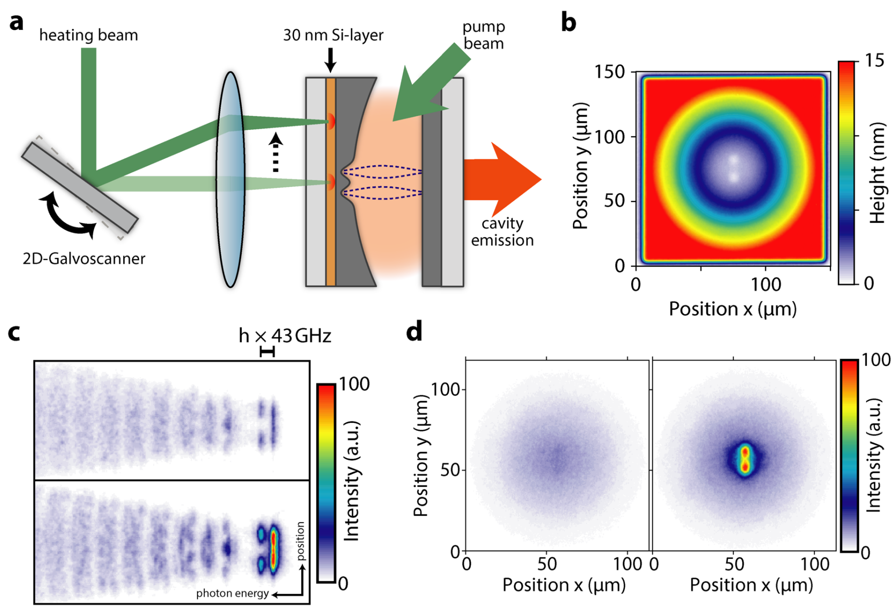

Figure 1. a Schematic of the experimental setup. **b** Height profile of one of the cavity mirrors generating a double well potential superimposed by a harmonic trapping potential. **c** Photon energy versus transverse position along the axis of the double well both below (top) and above (bottom) the threshold to a Bose-Einstein condensate, revealing a macroscopic occupation of the symmetric linear combination of the coupled double well eigenstates (right). **d** Spatial intensity profile below (left) and above (right) the Bose-Einstein condensation threshold.

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Enhanced thermalization of exciton-polaritons in optically generated potentials

Yoseob Yoon[1], Jude Deschamps[1], Loren N. Pfeiffer[2], Ken West[2], David W. Snoke[3], and Keith A. Nelson[1]

[1]**Department of Chemistry, Massachusetts Institute of Technology**
Cambridge, MA 02139, USA
[2]**Department of Electrical Engineering, Princeton University**
Princeton, NJ 08544, USA
[3]**Department of Physics, University of Pittsburgh**
Pittsburgh, PA 15218, USA

Equilibrium Bose-Einstein condensation (BEC) of exciton-polaritons has long been sought to distinguish it from polariton lasing. Toward this goal, we used three approaches to achieve the thermalized polariton distribution. First, a high-quality microcavity was used to increase the polariton lifetime longer than the thermalization time. This allowed the determination of the equilibrium phase diagram of polariton BEC [1]. Second, we tuned the cavity length so that the polaritons were more excitonic. We used two non-resonant pumps to study the detuning-dependent relaxation rate [2]. The spatial distributions shown in Fig. 1(a)-(b), along with energy-resolved momentum distributions, demonstrate that a larger exciton fraction facilitates relaxation toward the ground state. Third, we used an optically generated trap potential to confine polaritons and make them interact until they leaked out of the cavity [1, 2]. To identify the role of trapping, we measured the polariton energy distribution with all four pumps on, as shown in Fig. 1(c), and compared with the distributions measured individually with each pump. We found that the trapping plays an essential role in thermalization and relaxation of exciton-polaritons.

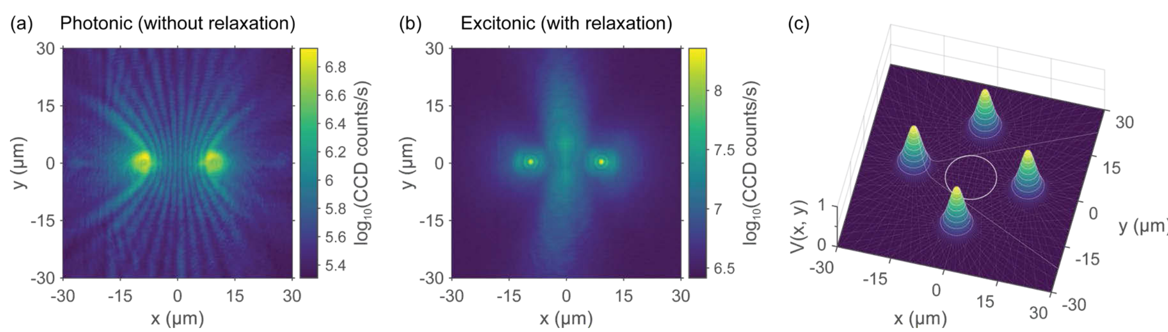

Figure 1. Two non-resonant pumps create (a) expanding ($k_x = \pm k_0$) and interfering condensates at photonic detunings and (b) a relaxed ($k_x = 0$) condensate at excitonic detunings. (c) The role of trapping in thermalization and relaxation processes is studied with four non-resonant pumps.

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Quantum Turbulent Structure in Light

Samuel N. Alperin[1,2], Abigail L. Grotelueschen[1], Mark T. Lusk[3], and Mark E. Siemens[1]

[1]Department of Physics & Astronomy, University of Denver
2112 East Wesley Avenue, Denver, Colorado 20210, USA

[2]Department of Applied Mathematics and Theoretical Physics, University of Cambridge
Centre for Mathematical Sciences, Wilberforce Rd, Cambridge CB3 0WA, UK

[3]Department of Physics, Colorado School of Mines
CSM Department of Physics, 1500 Illinois St., Golden, CO 80401

The superpositions of random plane waves are known to be threaded with vortex line singularities which form complicated tangles and obey strict topological rules. We use both numerical simulations and optical experiments to characterize these structures, finding that the velocity statistics match those of turbulent quantum fluids such as superfluid helium and atomic Bose-Einstein condensates. The distributions are shown to be independent of system scale. This raises deep questions about the general nature of quantum chaos and the role of nonlinearity in the structure of turbulence.

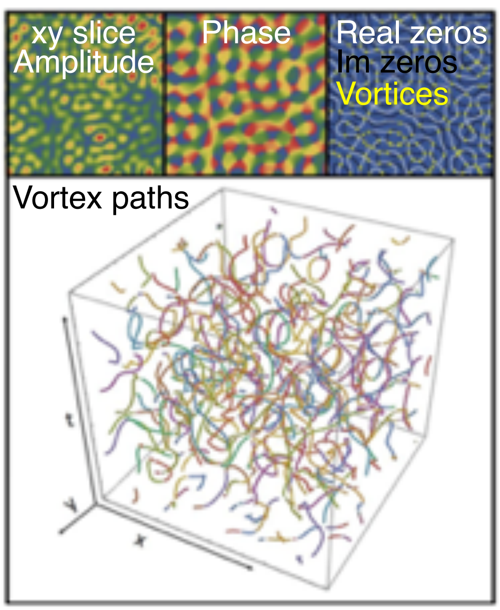

Fig. 1: Transverse amplitude (top left), phase (top middle) and real/imaginary zeros (top right) of a computationally-generated random wave. Singularities (marked in yellow) can be tracked with propagation, paths of which are marked in the bottom panel.

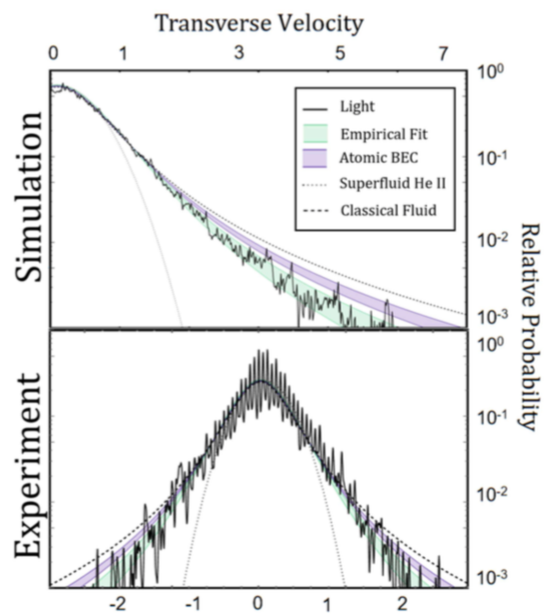

Fig. 2: Numerically simulated (top) and experimentally measured (bottom) probability distributions of transverse vortex velocities in random optical scatter (black), compared to traditional quantum fluids. Velocity units are normalized by distribution variance.

Acknowledgements
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A Supersonically expanding BEC: An expanding universe in the lab?

Gretchen K. Campbell

Joint Quantum Institute, NIST and UMD, College Park, Md 20742, USA

The massive scale of the universe makes the experimental study of cosmological inflation difficult. This has led to an interest in developing analogous systems using table top experiments. In a recent experiment, we model the basic features of an expanding universe by drawing parallels with an expanding ring-shaped Bose Einstein Condensate (BEC).We study the dynamics of a supersonically expanding ring-shaped BEC both experimentally and theoretically. The ring-shaped BEC serves as the background vacuum and phonons are the analogue to photons in the expanding universe. The expansion redshifts long-wavelength excitations, as in an expanding universe. After expansion, energy in a radial mode excitation leads to the production of bulk topological excitations – solitons and vortices – driving the production of a large number of azimuthal phonons. These complex nonlinear dynamics, fueled by the energy stored coherently in one mode, are reminiscent of a type of "preheating" that may have taken place at the end of inflation.

Quantum Many-Body Scars and Space-Time Crystalline Order from Magnon Condensation

Thomas Iadecola, Michael Schecter and Shenglong Xu

Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland, College Park, Maryland 20742 USA

We study the eigenstate properties of a nonintegrable spin chain that was recently realized experimentally in a Rydberg-atom quantum simulator. In the experiment, long-lived coherent many-body oscillations were observed only when the system was initialized in a particular product state. This pronounced coherence has been attributed to the presence of special ``scarred'' eigenstates with nearly equally-spaced energies and putative nonergodic properties despite their finite energy density. In this paper we uncover a surprising connection between these scarred eigenstates and low-lying quasiparticle excitations of the spin chain. In particular, we show that these eigenstates can be accurately captured by a set of variational states containing a macroscopic number of magnons with momentum π. This leads to an interpretation of the scarred eigenstates as finite-energy-density condensates of weakly interacting π-magnons. One natural consequence of this interpretation is that the scarred eigenstates possess long-range order in both space and time, providing a rare example of the spontaneous breaking of *continuous* time-translation symmetry. We verify numerically the presence of this space-time crystalline order and explain how it is consistent with established no-go theorems precluding its existence in ground states and at thermal equilibrium.

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Transient supersolid properties in an array of dipolar quantum droplets

Fabian Böttcher, Jan-Niklas Schmidt, Matthias Wenzel, Jens Hertkorn, Mingyang Guo, Tim Langen, and Tilman Pfau

5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, University of Stuttgart,
Pfaffenwaldring 57, 70569 Stuttgart, Germany

We study theoretically and experimentally the emergence of supersolid properties in a dipolar Bose-Einstein condensate. Both theory and experiment reveal a phase diagram with three distinct regimes - a regular Bose-Einstein condensate, incoherent and coherent arrays of quantum droplets. The latter exhibits a density modulation in the form of quantum droplets. These droplets are connected by a superfluid background, which leads to a robust phase coherence over the whole system. We further theoretically confirm that we are able to dynamically approach the ground state in our experiment and that its lifetime is only limited by three-body losses.

Acknowledgements

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Chaotic distribution of Fano-Feshabach resonances in Thulium atom

V.A. Khlebnikov1, D.A. Pershin1,2, V.V. Tsyganok1,2, E.T. Davletov1,2, E.S. Kalganova1,2,4, A.V. Akimov1,3,4

[1]**Russian Quantum Center**

Business center "Ural", 100A Novaya str., Skolkovo, Moscow, 143025, Russia

[2]**Moscow Institute of Physics and Technology**

Institutskii per. 9, Dolgoprudny, Moscow region, 141700, Russia

[3]**Texas A&M University**

4242 TAMU, College Station, Texas, 77843, USA,

[4]**PN Lebedev Institute RAS**

Leninsky prospekt 53, Moscow, 119991, Russia,

Lanthanides have a special place in field of quantum simulations with cold atom due to their unique properties, such as large orbital momentum and large magnetic momentum in the ground state [1]. Large orbital momentum in ground state leads to easily tunable interactions between cold atoms via low-field Fano-Feshbach resonances [2], while large magnetic moment leads to relatively strong dipole-dipole interactions.

We report on observation of low-field Fano-Feshbach resonances in ultra-cold polarized gas of thulium atoms. Two classes of resonances were observed: rising with temperature d-resonances and having opposite behavior – s-resonances, both shifting their position with temperature much like it been predicted previously. Since thulium atom has only one hole at f-shell the resonances are much less dense then in a case of Erbium and Dysprosium, but density of these resonances still follows chaotic statistics [3,4]. Besides, by carefully examine width dependence of the atomic temperature near the Fano-Feshabach resonance we were able to determine, that average scattering length of the thulium atom is positive and found magnetic field corresponding to zero crossing for the scattering length.

Besides, we report on our progress towards achieving Bose-Einstein condensation of Thulium atom.

Acknowledgements

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Zero and Finite Temperature Responses of 2D Dipolar Bosons at Non-zero Tilt Angles

<u>Khandker Quader</u> and Pengtao Shen

Kent State University
Department of Physics
Kent, OH 44242

Recent experimental advances in creating stable dipolar systems, including polar molecules with large dipole moments, have led to vigorous theoretical activities. After a brief overview, we discuss our work on dipolar bosons in 2D and quasi-2D geometry, and with non-zero tilt angles. Using Bogoliubov-de Gennes equations, we obtain the zero temperature (T) excitation spectrum of the condensate, and explore possible instabilities at different tilt angles, density and dipolar coupling. We then study the finite temperature response within the random phase approximation (RPA). At a given T, we find the system to be in a quasi-condensate phase, that undergoes a collapse transition at large tilt angles, and a finite momentum instability (signaling a striped phase) at sufficiently large dipolar coupling. We discuss possible application of our results to experiments. Finally, we discuss our study of the Kosterlitz-Thouless (KT) transition for an interacting 2D Bose gas using a finite-T Green's function approach. We numerically calculate the boson self-energy to 2nd order, as well as to all orders (bubble-sum) for the entire range of allowed momentum. This allows us to deduce a universal scaling parameter involving the critical superfluid transition temperature and density. We also obtain results for T_{KT} , superfluid density and the Landau critical velocity.

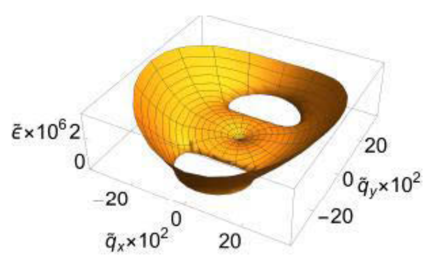

Figure 1. Calculated 2D dipolar boson spectrum at finite tilt angle, showing the roton instability as holes in the 3D plot of energy vs momentum in x-y direction.

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