Quantum-Atom Optics Beyond Bells
26-28 November 2008, Lorne, Victoria, Australia

Program of Talks and Posters

Time	Wednesday 26 November
08.25-08.30	**Welcome – Hans Bachor**
	Session Chair: Hans Bachor
08.30-09.00	**Wolfgang Ertmer** (Leibniz Universitat Hannover) ***QUEST: A New Centre for Quantum Engineering and Space-Time Research at the Leibniz Universität Hannover*** QUEST (Centre for Quantum Engineering and Space-Time Research) will concentrate on the advancement of quantum engineering and space-time research to gain a better understanding of the underlying physics and to improve or utilize resulting innovative methods in fundamental physics and applied fields. Accordingly, the activities of QUEST focus on four areas of research: Quantum Engineering, Quantum Sensors, Space-Time Physics, and Enabling Technologies. I will overview the Centre and its research fields. In addition I will present recent research results and ongoing work.
09.00-09.30	**P.D. Drummond, M.D. Reid, Qiongyi He, Scott Hoffmann** (ACQAO) ***Test of fundamental quantum theory with photons and atoms in the ACQAO Foundations Theory Group*** We develop criteria for mesoscopic superpositions, entanglement, EPR paradoxes and Bell's theorem for photonic and massive particles. We discuss potential applications to quantum memories, quantum cryptography and Brownian motion. As a practical proposal, we treat a novel type of interferometric quantum memory, which can encode a quantum state from a traveling wave photonic system onto a variety of other physical variables. As another example we develop the theory of quantum Brownian motion of a quantum particle in a BEC, in which the particle becomes entangled with the degrees of freedom of the BEC. Our goal is to work towards testing decoherence in both photonic and massive particle systems.
09.30-10.00	**Joachim Brand, Tania Haigh and Ulrich Zülicke** (Massey University) ***Topological solitons in double-ring Bose-Einstein condensates*** We consider a Bose-Einstein condensate in a double-ring trap under rotation. We find that all ground-state configurations are stable [1,2]. However, the phase diagram of the system shows a surprisingly complex structure with localized defects appearing in ground state configurations. The defects have the properties of topological solitons and can be seen as BEC analogs of Josephson Vortices. We study the dynamics of the defects under the influence of external fields. [1.] I. Lesanovsky and W. v. Klitzing, *Phys. Rev. Lett.* **98**, 050401 (2007). [2.] J. Brand, T.J. Haigh, and U. Zuelicke, arXiv:0805.4447 [quant-ph] (2008)
10.00-10.30	**Kris Helmerson** (NIST Gaithersburg) ***From thermal to quasi-condensate to superfluid: Observation of a 2D Bose-gas*** We present experimental results on a Bose gas in a quasi-2D geometry near the Berezinskii, Kosterlitz and Thouless (BKT) transition temperature. By measuring the density profile, *in situ*, and after time of flight, and the coherence length, we identify different states of the gas. In particular, we observe that the gas develops a bimodal distribution without long-range order. In this state, the gas presents a longer coherence length than the thermal cloud; it is quasi-condensed but is not superfluid. Experimental evidence indicates that we observe the superfluid transition (BKT transition).
10.30-11.00	**Coffee**
	Session Chair: Craig Savage
11.00-11.30	**Blair Blakie** (University of Otago) ***Critical properties of ultra-cold Bose gases*** Recently experiments have begun exploring the properties of ultra-cold Bose gases in the finite temperature critical regime. Examples of studies include: (i) low dimensional systems, where the critical regime extends over a wide temperate range, and evidence for an exotic superfluid transition has been found [1-2], and (ii) experiments examining the critical exponent for the emergence of phase coherence at the 3D BEC transition [3]. In this talk I will discuss progress on a theoretical description of the critical Bose gas using c-field techniques [4], and applications to these experiments. [1] Z. Hadzibabic, P. Kruger, M. Cheneau, B. Battelier, and J. Dalibard, Nature **441**, 1118 (2006). [2] P. Cladé, C. Ryu, A. Ramanathan, K. Helmerson, and W. D. Phillips, arXiv:0805.3519. [3] T. Donner, S. Ritter, T. Bourdel, A. Öttl, M. Köhl, and T. Esslinger, Science **315**, 1556 (2007). [4] P. B. Blakie, A. S. Bradley, M. J. Davis, R. J. Ballagh, and C. W. Gardiner, arXiv:0809.1487 .
11.30-12.00	**Brian P. Anderson** (University of Arizona) ***Spontaneous vortex formation in Bose-Einstein condensates*** Spontaneous topological defect formation is known to occur in the phase transitions of numerous physical systems. Recently, the spontaneous formation of vortices during Bose-Einstein condensation has also been observed and characterized (http://arxiv.org/abs/0807.3323, to appear in Nature). We will present the results and conclusions of this collaborative effort involving new experimental (Univ. of Arizona) and numerical (Univ. of Queensland) observations. We will then briefly discuss our ongoing efforts to characterize phase transition dynamics, vortex formation, and superfluid turbulence in Bose gases held in harmonic and annular traps with strong axial confinement.

12.00-12.30 **<u>M.J. Davis</u>, A.S. Bradley, G.M. Lee and B.P. Anderson** (ACQAO UQ)

Origin of topological defects in the formation of Bose-Einstein condensates

Solitons and vortices are examples of topological structures that may arise in Bose-Einstein condensates. The Kibble-Zurek mechanism [1] predicts that these objects arise from the merging of proto-condensates of different phases in the BEC phase transition, and recent experiments have observed the spontaneous appearance of vortices [2] in a pancake-like geometry, and solitons [3] in a cigar shape system. Here we use the stochastic Gross-Pitaevskii formalism [4] to study the formation of BECs in these geometries, identify the origin of the topological structures and relate it to the Kibble-Zurek mechanism.

[1] W. H. Zurek, Physics Reports **276**, 177 (1996).
[2] C. N. Weiler *et al*, Nature (in press), arXiv:0807.3323.
[3] P. Engels, private communication.
[4] C. W. Gardiner and M. J. Davis, J. Phys B **36**, 4731 (2003).

12.30-12.50 **<u>Mikko Möttönen</u>, Ville Pietilä, and Sami M.M. Virtanen** (Helsinki University of Technology)

Vortex pump for dilute Bose-Einstein condensates

The formation of vortices by topological phase engineering has been realized experimentally to create the first two- and four-quantum vortices in dilute atomic Bose-Einstein condensates. We consider a similar system, but in addition to the Ioffe-Pritchard magnetic trap we employ an additional hexapole field. By controlling cyclically the strengths of these magnetic fields, we show that a fixed amount of vorticity can be added to the condensate in each cycle. In an adiabatic operation of this vortex pump, the appearance of vortices into the condensate is interpreted as the accumulation of a local Berry phase. Our design can be used as an experimentally realizable vortex source for possible vortex-based applications of dilute Bose- Einstein condensates.

12.50-13.10 **<u>Andrew Sykes</u>, Matthew Davis, and David Roberts** (ACQAO UQ)

Force on a slow moving impurity due to thermal and quantum fluctuations in a 1D Bose-Einstein condensate

We study the drag force acting on an impurity moving through a 1D Bose-Einstein condensate in the presence of both thermal and quantum fluctuations. The results are exact to the level of the Bogoliubov approximation, of non-interacting quasi-particles. We find a weak but non-zero force is exerted on the impurity even at sub-critical velocities due to the surplus of fluctuations propagating downstream as opposed to upstream. The results are reminiscent of similar calculations done in the Born approximation for a 3D Bose-Einstein condensate [1]. A discussion of the quantum dynamics involved in the formation of persistent currents is included.

[1] D. C. Roberts and Y. Pomeau, Phys. Rev. Lett. **95**, 145303 (2005)

13.10-15.30 **Lunch**

14.10-15.10 **Lecture series: Introduction to Cavity QED** (three lectures).

Luis A. Orozco, University of Maryland

This series of lectures will introduce the basic ideas of Cavity QED in the optical regime to students and postdocs. There will be plenty of experimental illustrations.

<u>Lecture 1: Atoms in Cavities.</u>

15.30-16.00 **Coffee**

Session Chair: Andrei Sidorov

16.00-16.30 **Markus Oberthaler (invited)** (Universitat Heidelberg)

BEC in a Double Well – Mean Field Physics and Beyond

A Bose-Einstein condensate in a double well potential is a very simple system where mean field description, i.e., Gross-Pitaevskii equation, and the many particle description, i.e., two-mode Bose Hubbard, can be solved in a straight forward manner. In this talk the connection will be discussed in detail motivated by our recent experimental results. The observed Jospehson oscillations will be compared with the predictions of both descriptions. The realization of spin squeezing - phase coherent number squeezing - and its application to atom interferometry will also be presented.

16.30-17.00 **<u>B.V. Hall</u>, R. Anderson, C. Ticknor, P. Hannaford and A.I. Sidorov** (ACQAO SUT)

Two-Component Bose-Einstein Condensates on an Atom Chip

We report on a two component magnetically trapped rubidium system $|F=1,m_F=-1>$ and $|F=2,m_F=+1>$ which allows the realization of a trapped atomic clock through the application of two temporally separate, two photon (microwave + radiofrequency) $\pi/2$ pulses in a Ramsay type measurement. When the magnetic field defining the trap bottom is tuned to ~3.23G the differential Zeeman shift of the atomic resonance is first order independent. Further evaporative cooling yields a high density BEC with which we explore the effect of mean field dynamics using spatially selective Ramsey spectroscopy. While the density dependent collision shift induces appreciable dephasing over 100 ms timescales, moving just above T_c lengthens the dephasing time by an order of magnitude. Using this trapped ultra-cold atomic clock we motivate a precision measurement of the AC stark shift.

17.00-17.20	**<u>R. Anderson</u>, D.S. Hall, B.V. Hall, C. Ticknor, A.I. Sidorov** (ACQAO SUT) ***Nonequilibrium phase evolution and tunable interactions in a pseudo-spinor Bose-Einstein Condensate*** I will report on two complementary experiments studying two-component Bose-Einstein condensates. With the first, we are studying the spatio-temporal evolution of relative phase in the $\|F = 1, m_F = -1>$, $\|F = 2, m_F = +1>$ pseudo-spinor system of ^{87}Rb, using a micromagnetic trap on an atom chip. We are investigating two techniques involving (i) phase reconstruction using a spatially sensitive interferometric technique, and (ii) phase retrieval using a non-interferometric algorithm[1]. The rich dynamics of two-component condensates are governed by the intra- and inter-species s-wave scattering lengths. The second experiment explores the effect of tunable interactions between the $\|F = 1, m_F = +1>$ and $\|F = 2, m_F = -1>$ states in a crossed-beam optical dipole trap. We use an interspecies Feshbach resonance[2] that grants access to two regimes of miscibility between the components. Unlike quantum fluids consisting of mixed atomic species[3], we start from a well-defined nonequilibrium state and observe the time evolution, which is markedly different above and below the Feshbach resonance. [1]Y.E. Tan *et. al.*, Phys. Rev. E **68**, 066602 (2003). [2] E. G. M. van Kempen *et. al.*, Phys. Rev. Lett. **88**, 093201 (2002). [3] S.B. Papp *et. al.*, Phys. Rev. Lett. **101**, 040402 (2008).
17.20-17.40	**<u>Aephraim Steinberg</u>, Samansa Maneshi, Chao Zhuang, Chris Paul, and Luciano Cruz** (University of Toronto) ***<u>Coherence, Control, Correlations, and Chaos in Cold Atoms</u>*** We have been studying the preparation, preservation, and characterization of coherent vibrational states of Rb atoms in a shallow optical lattice. I will describe our work on tomography and control of these states, and results on using pulse echo to extract the decoherence time. The surprisingly fast echo decay has led us to adapt techniques from NMR and chemical physics, such as higher-order echoes and 2D pump-probe spectroscopy, to study the behaviour of frequency-frequency correlations. I will also show preliminary data on quantum control of the vibrational state via interfering one- and two-phonon excitations, and briefly describe the state of our other atom-optics experiments.
17.40-18.00	**<u>T. Müller</u>, X. Wu, A. Mohan, A. Eyvazov, Y. Wu and R. Dumke** (Nanyang Technological University, Singapore) ***<u>Towards a guided atom interferometer based on a superconducting atom chip</u>*** We evaluate the realization of a novel geometry of a guided atom interferometer based on a high temperature superconducting microstructure [1]. The interferometer type structure is obtained with a guiding potential realized by two current carrying superconducting wires in combination with a closed superconducting loop sustaining a persistent current. We present the layout and realization of our superconducting atom chip. By employing simulations we discuss the critical parameters of the interferometer guide in particular near the splitting regions of the matter waves. Based on measurements of the relevant chip properties we discuss the application of a compact and reliable on-chip atom interferometer. [1]: T. Müller et al, New J. Phys.**10**, 073006, (2008)
18.00-20.00	**Dinner (own arrangements)**
20.00-21.30	**Poster Session**

Time	Thursday 27 November
	Session Chair: Peter Hannaford
08.30-09.00	**J. F. Corney, M. Ögren and K. V. Kheruntsyan** (ACQAO SUT) ***Quantum dynamics of ultracold Fermions*** We study the real-time evolution of ultracold fermion systems using a first-principles approach to the quantum dynamics. The approach is based on the Gaussian phase-space representation [1] which is a generalisation of successful phase-space techniques for bosons. We will give an overview of how the representation enables simulation of real-time dynamics, and then consider its application to three different Bose-Fermi systems: (a) coherent dissociation of bosonic dimers into fermionic atoms, (b) Bose-Fermi mixtures in a double-well potential, (c) dispersive atom-light interactions. With these three examples, we illustrate the kind of physics that the quantum simulations can reveal (beyond the mean-field), as well as current limitations to the method. [1] J. F. Corney and P. D. Drummond, Phys. Rev. B 73, 125112 (2006).
09.00-09.30	**Hui Hu, Peter D. Drummond, and Xia-Ji Liu** (Renmin University, Beijing) ***Universal Thermodynamic Behaviour of Strongly Interacting Fermi Gases*** Experiments on ultra-cold atomic gases at nano-Kelvin temperatures are revolutionizing many areas of physics. Their exceptional adaptability and simplicity allows tests of many-body theory in areas long thought to be inaccessible, due to strong interactions. Ultra-cold Fermi gases are now providing new insight into the foundations of quantum theory. They are expected to exhibit a universal thermodynamic behaviour in the strongly interacting limit, independent of any microscopic details of the underlying interactions. In this talk, we present a systematic theoretical study of strong interacting fermions, using either different field-theoretic methods or a high-temperature cluster (virial) expansion technique. Pioneering measurements have dramatically confirmed our theoretical predictions, giving the first known evidence for universal fermion thermodynamics.
09.30-10.00	**F.M. Spiegelhalder, D. Naik, A. Trenkwalder, E. Wille, G. Hendl, F. Schreck and R. Grimm** (IQOQI, Innsbruck) ***Exploring ultracold Fermi mixtures of ^{6}Li and ^{40}K*** We are investigating ultracold mixtures of fermionic ^{6}Li and ^{40}K. ^{6}Li is efficiently evaporation cooled close to the 834 Gauss Feshbach resonance between its two lowest states. This ^{6}Li sample is a good thermal bath for sympathetic cooling of ^{40}K. We reach degeneracy of ^{6}Li in presence of ^{40}K in its lowest state. The long lifetime of this three fermion mixture across the ^{6}Li BEC-BCS crossover enables the utilization of ^{40}K as probe for the ^{6}Li behavior. Furthermore, we found 13 interspecies Feshbach resonances in various ^{6}Li-^{40}K internal state mixtures. Modeling enables the prediction of interaction properties of the system, including all Feshbach resonances and their properties. We are investigating LiK molecule creation using interspecies resonances.
10.00-10.30	**G. Veeravalli, E. Kuhnle, P. Dyke, and C.J. Vale** (ACQAO SUT) ***Bragg spectroscopy of a ^{6}Li Fermi gas in the BEC-BCS crossover*** We present a comprehensive study of the Bose-Einstein condensate to Bardeen-Cooper-Schrieffer (BEC-BCS) crossover in a gas of fermionic ^{6}Li using Bragg spectroscopy. A smooth transition from molecular to atomic spectra is observed with a clear signature of pairing at and above unitarity. These spectra probe the dynamic and static structure factors of the gas and provide a direct link to two-body correlations. We have characterised these correlations and measured their density dependence across the broad Feshbach resonance at 834 G. We have also investigated the temperature dependence of Bragg spectra near unitarity.
10.30-11.00	**Coffee**
	Session Chair: Karen Kheruntsyan
11.00-11.30	**Dmitry Petrov** (Orsay) ***Weakly bound heteronuclear dimers*** We consider collisional properties of weakly bound heteronuclear molecules (dimers) formed in a two-species mixture of atoms with a large mass difference. We focus on dimers containing light fermionic atoms as they manifest collisional stability due to an effective dimer-dimer repulsion originating from the exchange of the light atoms. In order to solve the dimer-dimer scattering problem we develop a new theoretical approach, which provides a physically transparent and quantitative description of this four-atom system in terms of three- and two-body observables. We calculate the elastic scattering amplitude and the rates of inelastic processes such as the trimer formation and the relaxation of dimers into deeply bound molecular states. Irrespective of whether the heavy atoms are bosons or fermions, the inelastic rate can be significantly lower than the rate of elastic collisions. Moreover, the measurement of the inelastic rate which is a four-body observable, can be an efficient and precise tool for determining three-body observables such as the three-body parameter, positions of Efimov states and their lifetimes.
11.30-12.00	**Michael Mark, Martin Berninger, Francesca Ferlaino, Steven Knoop, Hanns-Christoph Naegerl and Rudolf Grimm** (Universitat Innsbruck) ***Few-body physics with ultracold Cs atoms and molecules*** Ultracold atomic gases are versatile systems to study few-body physics because of full control over the external and internal degrees of freedom. The scattering properties can be controlled because of the magnetic tuneability of the two-body scattering length in the proximity of a Feshbach resonance and weakly bound dimers can be produced. We are able to routinely prepare trapped samples of atom-dimer and dimer-dimer mixtures at temperatures of 30-250nK. Particularly collision studies in atom-dimer mixtures allow new investigations on Efimov's prediction of the existence of universal trimer molecular states. We report on the observation of an atom-dimer resonance which we interpret as being induced by a trimer state. In atom-dimer mixtures with non-identical bosons we observe in collision measurements also a strong variation of the relaxation rate. Our findings might be because of the occurrence of exchange reaction processes. In dimer-dimer collisional studies the research is extended on four-body quantum systems.

12.00-12.30	**A.M. Martin, C. Ticknor, R.M.W. van Bijnen, N.G. Parker, D.H.J. O'Dell, A. Melatos and S.L. Cornish** (University of Melbourne) ***Properties of Ultra-Cold Dipolar Gases*** Recently significant experimental advances have been made in ultra-cold dipolar gas research. Within this context we present recent theoretical results on: (i) the stability of rotating dipolar dilute gas Bose-Einstein Condensates (BECs) and in the absence of rotation (ii) their anisotropic collapse dynamics. In the former case we show that the presence of dipolar interactions significantly alter the stability of a rotating dipolar BEC. In the later case we compare two analytical models to numerical integration of the Gross-Pitaevskii equation, enabling us to: (i) predict regimes of collapse and (ii) elucidate on the anisotropic nature of the collapse. Finally we will comment on future directions of research in both ultra-cold dipolar Fermi gases and BECs within the context of recent achievements in experimental ultra-cold polar molecule research
12.30-12.50	**Chris Ticknor** (ACQAO SUT) ***Ultracold Dipolar Scattering*** We explore the impact of the short-range interaction on the scattering of ground state polar molecules and study the transition from a weak to strong dipolar scattering over an experimentally reasonable range of energies and electric field values. In the strong dipolar limit, the scattering scales with respect to a dimensionless quantity defined by mass, induced dipole moment, and collision energy. The scaling has implications for all quantum mechanical dipolar scattering. Furthermore the universal scattering regime will readily be achieved with polar molecules at ultracold temperatures.
12.50-13.10	**Xia-Ji Liu, Hui Hu and Peter D Drummond** (ACQAO UQ) ***Strongly Interacting Polarized Fermi Gases*** Recently, superfluidity in trapped ultracold Fermi gases has become a hot topic in physics. The case of unequal spin populations has been the subject of considerable experimental and theoretical interest. This very new area has relevance to widely varying fields, from condensed matter physics, atomic molecular and optical physics, to particle and astro physics. Since BCS pairing requires an equal number of atoms in each spin state, the presence of spin population imbalance or polarization leads to exotic forms of pairing: the finite-momentum paired Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) state, the breached pairing or Sarma superfluidity, and phase separation. However, the true ground state of polarized fermionic superfluidity remains elusive, and has been the subject of debate for decades. Recent experimental observations open up intriguing possibilities for resolving this long-standing problem. Motivated by these significant experimental developments, we study the phase diagram and thermodynamics of the ground state and vortices in imbalanced, strongly interacting atomic gases near a broad Feshbach resonance. [1] Hui Hu, Xia-Ji Liu and P. D. Drummond, Phys. Rev. Lett. **98**, 070403 (2007) [2] Hui Hu, Xia-Ji Liu and P. D. Drummond, Phys. Rev. Lett. **98**, 060406 (2007). [3] Xia-Ji Liu, Hui Hu and P. D. Drummond, Phys. Rev. A **75**, 023614 (2007). [4] Xia-Ji Liu and Hui Hu, Europhys. Lett. **75**, 364-370 (2006). [5] Hui Hu and Xia-Ji Liu, Phys. Rev. A **73**, 051603(R) (2007). [6] Xia-Ji Liu, Hui Hu and P. D. Drummond, Phys. Rev. A **78**, 023601 (2008).
13.10-14.10	**Lunch**
	Session Chair: Ken Baldwin
14.10-14.40	**Joe Hope** (ACQAO ANU) ***Four-wave mixing in atom laser output and feedback control of trapped atoms*** Turning up outcoupling rates on atom lasers has long been shown to produce a range of multimode effects. We show that in metastable helium condensates operating in particular parameter regimes, it is possible to produce well-defined beams through a four-wave mixing (FWM) process. This FWM process is different to others that have been demonstrated in atom optics literature in that the source atoms are at zero velocity, and the energy is provided by the mean-field. The resulting scattered beams are well separated from the main atom laser in the 2-dimensional transverse atom laser profile. Numerical simulations of the system are in good agreement with the observed atom laser spatial profiles, and indicate that the scattered beams are generated by a four-wave mixing process, suggesting that the beams may be correlated. We also report on current progress towards finding methods of producing effective feedback control for a Bose-Einstein condensate.
14.40-15.10	**John Close** (ACQAO ANU) ***Atom Lasers: Flux Noise and Precision Measurement*** Over the last eight years we have concentrated on developing the atom laser as a useful tool for possible future precision measurement applications and for the investigation of fundamental physics. In this talk, I will give an overview of our past, present and future goals and the results we have obtained to date. Specifically, I will discuss noise, flux, detection and squeezing of atom laser beams.

15.10-15.30	**J.E. Debs, D. Döring, N.P. Robins, C.Figl, and J.D. Close** (ACQAO ANU) ***A high brightness atom laser for precision measurement*** Making the analogy with light, a coherent, bright beam of atoms out-coupled from a Bose-Einstein Condensate (BEC), now known as an atom laser [1-4], is a very promising tool for high precision atom interferometry [5]. We present results on a single mode, classically quiet atom laser produced from a Rb^{87} BEC, by coherently transferring atoms from a trapped to an untrapped state using an optical (two-photon) Raman transition, which couples the two hyperfine ground states of the Rubidium atom. While coupling between these two states has been achieved with microwave driven transitions [6], using Raman transitions brings several advantages. Raman transitions are able to transfer momentum to the atoms, increasing the atom laser brightness [7,8], and being optical in nature, have the potential to enable quantum state transfer of a squeezed optical state to the atomic beam. [1] M.-O. Mewes, *et al.*, Phys. Rev. Lett., **78**, p.582, (1997) [2] Y. Le Coq, *et al.*, Appl. Phys. B., **84**, p.627, (2006) [3] T. Bourdel, *et al.*, Phys. Rev. A., **73**, 043602, (2006) [4] A. Couvert, *et al.*, Arxiv preprint arXiv:0802.2601, (2008) [5] T. L. Gustavson, *et al.*, Phys. Rev. Lett. **78**, p.2046, (1997) [6] A. Öttl, *et al.*, Rev. Sci. Instrum., **77**, 063118, (2006) [7] E. W. Hagley *et al.*, Science, **283**, p.1706, (1999) [8] N. P. Robins *et al.*, Phys. Rev. Lett., **96**, 140403 (2006)
15.30-16.00	**S. Hodgman, R.G. Dall, M.T. Johnsson, K.G.H. Baldwin and A.G. Truscott** (ACQAO ANU) ***Single mode guiding of an atom laser beam*** Atoms coherently output-coupled from a Bose-Einstein condensate (BEC) form a coherent beam of matter waves, or `Atom laser'. Like its optical counterpart, the atom laser has the potential to revolutionise future atom interferometric sensors, in which a high flux of collimated atoms is required. Most condensates are confined in a magnetic potential, where to achieve maximum flux the atom laser beam is outcoupled from the centre of the BEC. This leads to atoms in the atom laser beam probing the high density region of the BEC via s-wave interactions and experiencing a large repulsive force (so-called `mean field' repulsion). These interactions strongly distort the atom laser beam, resulting in a far from ideal spatial profile that exhibits a double peaked structure. A method to alleviate this problem is to use an optically trapped BEC. In such case an atom laser is produced by simply turning down the optical power of the trap and letting atoms fall out of the spatial minimum of the trap where the atomic density is low. Furthermore, by not extinguishing the optical trap completely the atom laser beam experiences a weak confining potential that acts like an optical fibre to guide the atoms.
16.00	**Coffee break and ACQAO CI meeting** 16.30-17.30 **Lecture series: Introduction to Cavity QED** **Luis A. Orozco,** University of Maryland **Lecture 2: Time Correlations and Feedback**
19.00	**Workshop Dinner**

Time	Friday 28 November
	Session Chair: Bryan Dalton
08.30-09.00	**Luis A. Orozco** (University of Maryland) ***From photon bursts to quantum beats. Experiments in cavity QED.*** The interaction of a Rb atom with the two orthogonal polarization modes of an optical cavity presents new possibilities for single atom detection and the evolution of quantum beats in the ground state. Experiments with moderate coupling between the atom and the modes show conditional dynamics visible through correlation function measurements. Work done in collaboration with Matthew Terraciano, David Norris, Rebecca Olson, Jietai Jing, Arturo Fernandez, Pablo Barberis, and Eric Cahoon. Supported by NSF and NIST
09.00-09.30	**H.J. Carmichael** (University of Auckland) ***The Jaynes-Cummings Model and its Superconducting Tale*** The Jaynes-Cummings model is well known as the elementary model in quantum optics of the quasi-resonant interaction of a mode of the electromagnetic field and matter, must usually a two-state atomic resonance. It is a central model of cavity quantum electrodynamics (cavity QED), where it has been applied to investigations from microwave frequencies to optical frequencies, and, in an opto-mechanical analog, to trapped ions. Recently, in a series of impressive experiments the Jaynes-Cummings model has been realized in circuit cavity QED with a superconducting qubit substituting for the two-state atom. In some cases, features of the model that have never been observed in conventional cavity QED experiments are seen. This talk will review these recent results and their background in optical frequency cavity QED. Potential extension of their exploration of the Jaynes-Cummings model will also be discussed
09.30-10.00	**Scott Parkins** (University of Auckland) ***Conditional Quantum Dynamics in Cavity QED with Microtoroidal Resonators*** Single, ultra-cold atoms can now be made to interact strongly and controllably with single-photon light fields confined within microscopic optical resonators. Moreover, new resonator configurations, such as lithographically fabricated monolithic microresonators, hold great promise for the implementation of quantum networks and quantum logic with atoms and photons. In this talk I describe some recent theoretical and experimental results for cavity QED with microtoroidal resonators, including the demonstration of conditional quantum dynamics with single photons and single atoms.
10.00-10.30	**J.J. McFerran, A. Lurie, C. Perrella, C.R. Locke, F. Benabid and A.N. Luiten** (University of Western Australia). ***Compact Laser Clocks and Combs*** Clocks and oscillators are key enabling technologies for precision measurements in industrial and academic environments. The very best performing examples of these devices are typically large, delicate and complex. We have been pursuing two different routes for reducing the size and complexity of these devices so that they can be more widely deployed in industrial applications. The first approach makes use of an atomic beam of Calcium combined with an all-diode laser interrogation and read-out system for a quantum limited optical frequency standard with a performance in the 10^{-13} fractional frequency regime. The second approach is based around high-resolution nonlinear spectroscopy of iodine or Rubidium vapour that has been trapped in the hollow-core of photonic crystal fibre. This fibre approach confers excellent overlap between the light and absorber and leads to high signal to noise resonances in a compact geometry. In both approaches we can convert the output of the optical clocks into the optical domain using a mode-locked fibre frequency comb
10.30-11.00	**Coffee**
	Session Chair: Alexander Akulshin
11.00-11.30	**Jiri Janousek, Katherine Wagner, Vincent Delaubert, Hongxin Zou, Charles Harb, Nicolas Treps, Jean-Francois Morizur, Ping Koy Lam, Hans-A. Bachor** (ACQAO ANU) ***Spatial and multimode entanglement for laser beams*** Entanglement is one of the most interesting features of quantum mechanics, with the original thought experiment that resulted in the EPR paradox using the conjugate spatial observables of position and momentum. Here we present our results for spatial and multimode entanglement in the continuous variable regime. We show how we have entangled the spatial properties, or position and momentum, of a laser beam, by using squeezed light in higher order spatial modes. Two different criteria for entanglement were measured, for both the Inseparability of the system and the measurement of EPR entanglement. We also show results for multimode entanglement, where different spatial modes, the TEM10 and TEM01 modes, are entangled.
11.30-12.00	**M. Hosseini, G. Hétet, B.M. Sparkes, J.J. Longdell, M.J. Sellars, D. Oblak, P.K. Lam, B.C. Buchler** (ACQAO ANU) ***The "gradient echo memory" with three-level atoms.*** Photon echo systems are promising for quantum memory, especially when there is no a-priori knowledge of the state to be stored. Our photon echo scheme, the Gradient Echo Memory (GEM), is based on an atomic frequency gradient along the axis of light propagation. A signal to be stored is decomposed into its Fourier components and stored in an atomic ensemble as a Fourier spectrum along the length of the storage medium [1]. GEM for two-level atoms has recently been demonstrated [2]. We propose a three-level GEM scheme using a far detuned Raman coupling to long-lived ground states [3]. We present an experimental realization of our proposal using rubidium atoms in a warm vapour cell and discuss future prospects for this technique. [1] G. Hétet, J. J. Longdell, M. J. Sellars, P. K. Lam, B. C. Buchler, arXiv:0801.3860v1 [2] G. Hétet, J. J. Longdell, A. L. Alexander, P. K. Lam, and M. J. Sellars, Phys. Rev. Lett. 100, 023601 (2008). [3] G. Hétet, M. Hosseini, B. Sparkes, D. Oblak, P. K. Lam, B. C. Buchler, arXiv:0806.4258v2

12.00-12.20	**B.P. Lanyon, M.P. Almeida, M. Barbieri, and A.G. White** (University of Queensland) ***Quantum computing with zero entanglement*** Quantum computing promises an exponential speed-up compared to classical computation for a range of problems. There is a widespread perception that entanglement is what makes quantum computing powerful, which is certainly true for pure states[1,2]. A decade ago Knill and Laflamme proposed an alternative model, where a single pure qubit interacts with a register of completely mixed qubits: *deterministic quantum computation* (DCQ1)[3] . Although this model does not allow universal quantum computation, it nevertheless can potentially efficiently perform important computational tasks thought to be classically intractable[3-8]. DCQ1 is attractive both experimentally, since it *dramatically* reduces coherence requirements, and conceptually, since intriguingly entanglement is, at most, marginally present[9]. We implement the DQC1 algorithm for estimating the normalised trace of a unitary matrix[3,8-10]; we use linear optic circuitry, compiling our circuits with a technique that takes shortcuts through higher dimensions[11]. Despite zero measured entanglement, we demonstrate that a speed-up is still present[12]. The nonclassicality of the outputs is captured by the quantum *discord*[13], which vanishes only when a classical efficient simulation of our circuit is possible. It seems that discord may play an important role in understanding the power of quantum computing. [1]. R. Josza, N. Linden, *Proc. R. Soc. London A* **459**, 2011 (2003). [2]. G. Vidal, *Phys. Rev. Lett.* **91**, 147902 (2003). [3]. E. Knill, R. Laflamme, *Phys. Rev. Lett.* **81**, 5672 (1998). [4]. D. Poulin, R. Blume-Kohout, R. Laflamme and H. Olivier, *Phys. Rev. Lett.* **92**, 177906 (2004). [5]. E. Knill, R. Laflamme, *Inf. Proc. Lett.* **79**, 173 (2001). [6]. P. W. Shor, S. P. Jordan, *arXiv:*0707.2831 (2007). [7]. R. D. Somma, S. Boixo, *arXiv:*0708.1330 (2007). [8]. A. Datta, S. T. Flamina, C. M. Caves, *Phys. Rev. A* **72**, 042316 (2005). [9]. A. Datta, G. Vidal, *Phys. Rev. A* **75**, 042310 (2007). [10]. A. Datta, A. Shaji, and C. M. Caves, *Phys. Rev. Lett.* **100**, 050502 (2008). [11]. B. P. Lanyon, *et al.*, *arXiv:*0804.0272v1 (2008). [12]. B. P. Lanyon, M. Barbieri, M. P. Almeida, A. G. White, *arXiv:0807.0668* (2008). [13]. H. Olivier, W. H. Zurek, *Phys. Rev. Lett.* **88**, 017901 (2001).
12.20-12.40	**A. Politi, J.C.F. Matthews, A. Laing, A.S. Clark, J. Fulconis, M.J. Cryan, J.G. Rarity, A. Stefanov, S. Yu, G.D. Marshall, M. Ams, P. Dekker, M. Withford, W.J. Wadsworth, T. Rudolph and J.L. O'Brien** (University of Bristol) ***Silica-on-Silicon Waveguide Quantum Circuits*** We have developed an integrated waveguide approach to photonic quantum circuits [1]. We demonstrate high-fidelity silica-on-silicon integrated optical realizations of key quantum photonic circuits, including two-photon quantum interference with a visibility of 94.8(5)%; a controlled-NOT gate with an average logical basis fidelity of 93.3(2)%; and a path entangled state of two photons, relevant to quantum metrology, with fidelity >92%. We use these devices to demonstrate multi-photon effects relevant to quantum metrology [2] and quantum information processing [3]. The monolithic nature of these devices means that the correct phase can be stably realized in what would otherwise be an unstable interferometer, greatly simplifying the task of implementing sophisticated photonic quantum circuits. We fabricated 100's of devices on a single wafer and find that performance across the devices is robust, repeatable and well understood. [1] A. Politi, M. J. Cryan, J. G. Rarity, S. Yu, J. L. O'Brien, *Science* **320**, 646 (2008) [2] T. Nagata, R. Okamoto, J. L. O. Brien, K. Sasaki, S. Takeuchi, *Science* **316**, 726 (2007) [3] J. L. O'Brien, *Science* **318**, 1567 (2007)
12.40-13.00	**R. Poldy, B.C. Buchler and J.D. Close** (ACQAO ANU) ***Single atom detection with optical cavities*** We aim to develop high quantum efficiency (QE) detectors for single neutral ground state atoms. Optical cavities have already been used to detect such single atoms, but the focus of previous work has been on strongly coupled cavity QED experiments [1-3]. Our work aimed to discover whether strong coupling is really required for high detection efficiency, and if not, how "bad" the cavity can be. We modelled the detection using the Master equation as a function of a broad range of parameters, including atom-probe and cavity-probe detunings, probe power, and cavity finesse [4]. Our model shows that relatively low finesse cavities (~10^4) can provide comparable performance to cavities of finesse 10 times larger, although we require optical power levels beyond the range of the normal APD detection. We predict single atom detection QE of >99% with a red-detuned laser that 'sucks' atoms into the antinodes of the cavity standing wave pattern. [1] H.J. Kimble, Phys. Scripta **76**, 127 (1998) [2] P. Münstermann *et al*, Opt. Comm. **159**, 63 (1999) [3] A. Öttl *et al*, Rev. Sci. Instrum. **77**, 063118 (2006) [4] R. Poldy, B.C. Buchler and J.C. Close, Phys. Rev. A **78**, 013640 (2008)
13.00-15.30	**Lunch** 14.00-15.00 **Lecture series: Introduction to Cavity QED** **Luis A. Orozco,** University of Maryland **Lecture 3: Conditional Field.**
15.30-16.00	**Coffee**
	Session Chair: Russell McLean
16.00-16.30	**A. Ullah, S.A. Whalen, J-A. Currivan and M.D. Hoogerland** (University of Auckland) ***Loschmidt echos in a delta-kicked rotor*** We investigate the scope for reversing the chaotic dynamics of the delta-kicked rotor, as recently proposed. Initially, we apply a set of n kicks with a period $T = \pi/(2\omega_r) + \varepsilon$, subsequently we wait for a time $T' = \pi/(4\omega_r)$ and finally a set of n kicks with a period $T'' = \pi/(2\omega_r) - \varepsilon$. For atoms with a small momentum, this second sequence should exactly reverse first sequence. As this is valid only for small momenta, the final velocity distribution at zero momentum is more narrow than the initial distribution, but should achieve the same height. Although this is not true cooling, as there is no increase in phase space density, this has been dubbed "Loschmidt cooling"

16.30-17.00	**Tristram Alexander** (ACQAO ANU) ***Nonlinear phenomena in Bose-Einstein condensates*** I will present some of the latest work which has been carried out at the ACQAO theory node in the Nonlinear Physics Centre, including work on spinor condensates, Bose-Einstein condensates in time-varying potentials, and condensates in optical lattices. Our study of spinor condensates has revealed that a homogeneous magnetic field may dramatically change the properties of an antiferromagnetic condensate, with the possibility of the spontaneous formation of spin domains. We have also found that spinor condensates behave quite unexpectedly when subjected to a moving defect, with only one active speed of sound identified. Our work on time-varying potentials has found that the ratchet effect may be used to move and sort solitons in an attractive condensate, while on-going work on BEC in optical lattices has revealed that a condensate may flow through a lattice in self-induced waveguides. In all cases the behaviour emerges due to the intrinsic nonlinearity of the condensate.
17.00-17.20	**Lincoln Turner, Yingmei Liu, Steven Maxwell, Sebastian Jung and Paul Lett** (Monash University) ***New measurements and new physics with spinor BECs*** Holding Bose-Einstein condensates (BECs) in far off-resonant optical dipole traps leaves the condensate's spin free. Such spinor condensates show complex interaction between spin and spatial structure such as spontaneous symmetry breaking into ferromagnetic domains. The spatial coupling can be suppressed, allowing the BEC to behave as "one big spin". Faraday spectroscopy provides a promising minimally-destructive measurement of this macroscopic spin state. As well as displaying the obvious Larmor precession in a magnetic bias field, the spin state is modulated by spin-mixing collisions. We present a continuous Faraday measurement of both Zeeman populations *and* phases of the evolving spinor condensate, distinguishing the two regions of the spin-mixing phase space. The single-spatial mode spinor condensate exhibits extraordinarily long coherence times of several seconds. We have studied the decoherence processes using continuous measurements of the evolving condensate, opening the path to spontaneous spin squeezing and measurement-induced squeezing experiments.
17.20-17.40	**A S Bradley** (University of Otago) ***Scale invariant thermodynamics of a toroidally trapped Bose gas*** We consider a system of noninteracting bosonic atoms in an axially symmetric harmonic trap augmented with a Gaussian optical potential [1]. We determine the ideal gas thermodynamics of the system for configurations ranging from the flattened harmonic trap through to the deep toroid regime. In the deep toroid regime the density of states, and thus all ideal gas thermodynamics, becomes independent of the toroidal size. We consider corrections to the scale invriant T_c caused by interactions, finite particle number and residual gravitational forces. The first order interaction shift [2] is the dominant correction and is also found to be size invariant in the deep toroid regime. We find that adiabatic loading has only a small effect on the condensate fraction for the ideal gas, indicating that loading into the scale invariant regime may be experimentally practical. Implications for Kibble-Zurek mechanism studies in toroidal traps are also investigated. 1. *Spontaneous vortices in the formation of Bose-Einstein condensates,* C. N. Weiler, T. W. Neely, D. R. Scherer, A. S. Bradley, M. J. Davis, B. P. Anderson, to appear in Nature, **arXiv:0807.3323** 2. S. Giorgini, L. P. Pitaevskii, andS. Stringari, Phys. Rev. A**54**, R4633(1996).
17.40-18.00	**S. A. Haine and M. T. Johnsson** (ACQAO ANU, UQ) ***Generating number squeezing in a Bose-Einstein Condensate through nonlinear interaction.*** We develop a scheme to create number squeezing in a Bose-Einstein condensate in an optical trap by utilizing the nonlinear atomic interactions as well as interference between two hyperfine levels. If the s-wave scattering lengths differ between the various Zeeman magnetic sublevels, squeezing well below the quantum limit can be obtained, even if the initial noise is very much higher than the quantum limit. We model our scheme using a multimode quantum field approach with realistic parameters, and find agreement with a simple analytic model in certain regimes. We also discuss possible experimental realizations and consider which atomic species will give the best results. [1] M. T. Johnsson and S. A. Haine, Phys. Rev. Lett. **99** 010401 (2007).
18.00	**Workshop close**

	Posters
1	**<u>Ville Pietilä</u> and Mikko Möttönen** (Helsinki University of Technology) ***Non-Abelian magnetic monopole in a Bose-Einstein condensate*** Recently, an effective non-Abelian magnetic field with a topology of a monopole was shown to emerge from the adiabatic motion of multilevel atoms in spatially varying laser fields [J. Ruseckas et al., Phys. Rev. Lett. 95, 010404 (2005)]. We study this monopole in a Bose-Einstein condensate of degenerate dressed states and show that it gives rise to a monopole with the same topological charge in the pseudospin texture of the condensate ground state. Furthermore, we derive a gauge invariant topological charge describing the total magnetic charge of the system and show that textures with non-vanishing total charge can exist. Finally, we discuss possible ways to detect these states in experiments.
2	**<u>Joshua P. Beardmore</u>, Adam J. Palmer, and Robert T. Sang** (Griffith University) ***Production of a pure metastable neon beam for studies into UV free atom lithography*** We present the characterization of a series of atom optical elements designed to produce a pure atomic beam of neon atoms in the $^3P_2$ metastable state. The atomic source is a gas discharge system which creates a beam that consists of neutral atoms, UV photons, ion, electrons and atoms in the metastable state of interest [1]. Charged products are deflected out of the beam via electrostatic deflection plates. The atom optical elements following the deflection plates consist of a two-dimensional optical collimator [2] and a Zeeman slower to reduce the transverse and longitudinal velocities of the beam respectively. The last element in the beam line is a multi-element magnetic guide to steer the metastable atoms. The magnetic guide displaces the metastable atoms from the UV and ground state atom components of the beam. The resulting beam will be utilised for studies into nanofabrication using atom lithographic techniques [3, 4]. Atom lithography is one of two main approaches to nanofabrication using atoms. This technique uses a beam of metastable rare gas atoms to damage an alkanethiol photo-resist coated target sample which can then be chemically etched to transfer the patterning onto an underlying layer. The sources used to create such metastable beams also generate UV photons with sufficient energy to damage the photo-resist [5]. This damage leads to undesirable effects in pattern formation and it is therefore desirable to perform the lithography in a UV free environment. This is the impetus behind the current research being undertaken and we will report on new results for this new atomic beam system as well as give an update on our atom lithography experiments. [1] M. Baker, A. J. Palmer and R. T. Sang, *Meas. Sci. Technol.* **14**, N5 (2003). [2] M. D. Hoogerland, J. P. J. Driessen, E. J. D. Vredenbregt, H. J. L. Megens, M. P. Schuwer, H. C. W. Beijerink and K. A. H. van Leeuwen, *Appl. Phys. B: Lasers Opt.* **62** 323 (1996). [3] M. Baker, A. J. Palmer, W. R. MacGillivray and R. T. Sang, *Nanotechnology* **15**, 1356 (2004). [4] A. J. Palmer, M. Baker and R. T. Sang, *Nanotechnology* **17** (2006) 1166. [5] R. R. Chaustowski, V. Y. F. Leung and K. G. H. Baldwin, *Appl. Phys. B: Lasers Opt.* **86** 491 (2007)
3	**<u>Q.Y. He</u>, M. D. Reid, E. Giocobino, J. Cviklinski and P. D. Drummond** (ACQAO SUT) ***Time-Symmetric Dynamical Quantum Memories*** In a recent paper [submitted to PRA], we proposed a dynamical approach to quantum memories using an oscillator-cavity model. This overcomes the known difficulties of achieving high quantum input-output fidelity with storage times long compared to the input signal duration. The step-switching or gating of the coupling or detuning generated asymmetric mode-shapes. In the present paper, we perform the same analysis for the symmetric pulse propagation. We use a generic model of the memory response, which is applicable to any linear storage medium ranging from a superconducting device to an atomic medium. This shows that with temporal modulation of coupling and/or detuning, it is possible to mode-match to nearly arbitrary input and output mode-shapes, including time-symmetric pulses that are well-suited to laser and microwave pulse generators. We show how a dynamical quantum memory can surpass the relevant classical memory bound, while retaining a relatively long storage time.
4	**<u>S.K. Schnelle</u>, K.J. Weegink, L. Humbert, E.D. van Ooijen, M.J. Davis, N.R. Heckenberg and H. Rubinsztein-Dunlop** (University of Queensland) ***Ultra-cold atoms in a time averaged optical potential*** We demonstrate the loading of a sample of ultra-cold atoms into a scanning beam trap proposed by our group [1]. The scanning beam trap for versatile optical potentials enables the creation of arbitrary two dimensional potentials to be used with ultra-cold atoms. Arbitrary potentials are a helpful tool when researching properties of ultra-cold gases that need specifically tailored potentials. An example of those properties would be superfluidity of Bose-Einstein condensates which is best investigated in toroidal traps. Another example is the investigation of tunneling through a thin barrier in Bose-Einstein condensates which needs multiple well potentials. In this presentation we will show the trap design based on a far-red detuned laser beam scanned by an acousto-optical modulator (AOM) as well as a feed forward loop to control the spatial intensity of the laser beam. We also show that the lifetime in the trap and the heating effects caused by the time averaged scanning of the beam are sufficiently low to perform experiments on ultra-cold atoms. [1] S. K. Schnelle, E. D. van Ooijen, M. J. Davis, N. R. Heckenberg, and H. Rubinsztein-Dunlop, Opt. Express, **16**, 1405 (2008)
5	**<u>Geoffrey M. Lee</u>, Ashton S. Bradley and Matthew J. Davis** (ACQAO UQ) ***Coherence properties of a continuous-wave atom laser at finite temperature*** In order to create a truly continuous-wave (cw) atom laser, a mechanism for replenishing the Bose-Einstein condensate reservoir must be implemented. One such mechanism is to replenish a thermal reservoir undergoing continuous evaporative cooling. Using the stochastic Gross-Pitaevskii (SGPE) formalism [1], we have modelled a one-dimensional cw atom laser with Raman outcoupling incorporating this pumping mechanism. The SGPE formalism separates the full system into two regions at a specific energy cut, with the high energy region approximated as the thermal bath, with a fixed temperature and chemical potential. We have found the steady state of the atom laser model, and calculated the properties of the output beam. In particular, the coherence properties and linewidth of the beam have been calculated as functions of temperature and outcoupling rate. These results can provide an optimal set of parameters for operating a cw atom laser. [1] C.W. Gardiner, J.R. Anglin and T.I.A. Fudge, J. Phys. B, 35, 1555 (2002); C.W. Gardiner and M.J. Davis, J. Phys. B. 36, 4731 (2003).

6 **N.P. Robins, D. Döring, G.R. Dennis, C. Figl, and J.D. Close** (ACQAO ANU)

A pumped atom laser in the continuous and pulsed regimes

Research into atom lasers is slowly taking a foot-hold both in Australia [1,2,3] and overseas [4]. As a fundamental system atom lasers offer a fascinating atomic analogue of the optical laser, and in addition show great promise for interferometric applications [5].
We present our recent work on the development of the first pumped atom laser. Atoms are pumped from a source cloud to a lasing mode by a Bose enhanced irreversible transition [1]. The source cloud and the lasing mode are two spatially separated Bose-Einstein condensates. We have realised the pumping mechanism in the continuous and pulsed regimes. The experiment is a necessary step in producing a continuous, narrow linewidth atom laser. It is an intriguing challenge to use the combination of two separated Bose-Einstein condensates and coherent internal state control to set up an atomic local oscillator. Squeezing the atom laser output is a promising way to increase the interferometric sensitivity.

[1] N.P. Robins, et al, Nature Physics, Published online: 11 July 2008; doi:10.1038/**nphys1027**
[2] O. Vainio et al, Phys. Rev. A **73**, 063613 (2006).
[3] C.J. Dedman et al. Rev. Sci. Instr. **78**, 024703 (2007).
[4] T. Bourdel et al. Phys. Rev. A **73**, 043602 (2006).
[5] eg. Coherence, Squeezing and Entanglement for Precision Measurements with Quantum Gases Levico (Trento), 3-5 April, 2008

7 **D. Döring, J. Debs, N.P. Robins, C. Figl, and J.D. Close** (ACQAO ANU)

A continuous free-space coherent atom interferometer

Atomic interferometers are devices of steadily increasing importance in areas such as precision measurements and fundamental studies [1]. Atom interferometers are typically based on cold thermal atoms [2,3]. The use of coherent (Bose-condensed) atoms offers significant advantages concerning the achievable signal-to-noise ratio and the utilisation of quantum mechanical effects.
In pursuit of a freely propagating *coherent* interferometer we have applied a two photon Raman coupling mechanism to an atom laser beam. The two (first-order) magnetically insensitive internal ground states of ^{87}Rb effectively form a two-level system whose internal (atomic population) and external (atomic momentum) degrees of freedom can be coherently controlled by the 6.8 GHz Raman laser beams. By focussing the optical coupling beams, spatially selective addressing of the atom laser beam is achieved, allowing us to accomplish a Ramsey sequence and analyse the corresponding interference fringes.

[1] A. Miffre *et al.,* Phys. Scr. **74**, C15 (2006).
[2] J.B. Fixler *et al.,* Science **315**, 74 (2007).
[3] Pierre Cladé *et al,* PRL **96**, 033001 (2006).

8 **P. A. Altin, N. P. Robins and J. D. Close** (ACQAO ANU)

Sympathetic cooling of ^{85}Rb

The ability to manipulate the scattering length of ultra-cold atoms, via a magnetic field Feshbach resonance, has led to a number of important scientific breakthroughs, including Bose-Einstein condensation of molecules [1], studies of the BCS/BEC crossover regime [2], and non-interacting coherent interferometry [3].
Rubidium 85 has a broad, low field Feshbach resonance around 155G making it an ideal candidate for our experiments with interaction free atom lasers and investigations of systems such as the 'Bosenova' [4]. We report on our progress towards producing a Bose-Einstein condensate of ^{85}Rb via sympathetic cooling with ^{87}Rb using a combination of magnetic and optical trapping.

[1] S. Jochim et al, Science **302**, 2101, (2003).
[2] C. A. Regal, M. Greiner, D. S. Jin, Phys. Rev. Lett. **92**, 040403, (2004).
[3] M. Fattori et al, Phys. Rev. Lett. **100**, 080405 (2008).
[4] J. L. Roberts et al, Phys. Rev. Lett. **86**,4211 (2001).

9 **Andy Ferris, Murray Olsen, Eric Cavalcanti and Matthew Davis** (ACQAO UQ)

Detection of continuous variable entanglement without a coherent local oscillator

We propose three criteria for continuous variable entanglement between two many-particle systems. These criteria are based on homodyne measurements and allow for local oscillators in an arbitrary quantum state (i.e. not necessarily coherent). We find that falsely assuming a coherent local oscillator can lead to mistakenly identifying the presence of entanglement, which we demonstrate in simulations with 100 particles. We also find that large number fluctuations do not prevent the observation of entanglement, and that even chaotic (thermal) initial states can be used in potential quantum optical or quantum-atom optical experiments. Our results are important for quantum information experiments with realistic Bose-Einstein condensates or in optics with arbitrary photon states.

10 **L. Humbert, E.D. van Ooijen, N. Heckenberg, H. Rubinsztein-Dunlop** (University of Queensland)

Towards an all-optical BEC in optical toroidal traps

I will present the current status of an all-optical BEC experiment at UQ. In a magnetic quadrupole field 87 Rb atoms are pre-cooled and transferred into an optical dipole trap [1] to reach quantum degeneracy. Afterwards the sample is loaded into an optical toroidal trap. This optical toroidal trap consists of a light sheet to freeze out one direction of motion combined with laser beams perpendicular to the light sheet provide a ring shaped potential. Within this project we are using two methods to create the ring shaped potential. One method uses a fast scanning beam [2], whereas the other method uses the attractive and repulsive interaction of light with atoms of red and blue detuned beams, which are overlapped in a fiber [3]. The ring diameter can change from a few ten microns to a few hundred microns, which is adjustable by the choice of the parameters of the used lasers such as wavelengths, waists and powers. Our estimations show that it will be possible to reach the 1D regime in which the interaction along the ring is dominating. Toroidal traps have due to its geometry periodic boundary conditions and are therefore interesting for all applications and physical model systems that require those. Recently persistent currents of a super fluid BEC has been successfully demonstrated by K. Helmerson [4] at NIST in W.D. Phillips research group. The investigation of quantum degenerated Bose gases in toroidal traps opens research to interesting and comprehensive physics.

[1] S.J.M. Kuppens et al., PRA 62, 013406, (2000)
[2] S. K. Schnelle et al., Optics Express, 16, 3, pp. 1405-1412, (2008)
[3] F. Moscatelli et al., PRA 76, 043404 (2007)
[4] K. Helmerson et al., Nuclear Physics A, 790 pp. 705c-712c, (2007)

11 **Michael C. Garrett, Adrian Ratnapala, Erik D. van Ooijen, Chris J. Vale, Otto Vainio, Norman R. Heckenberg, Halina Rubinsztein-Dunlop, and Matthew J. Davis** (University of Queensland)

Bose-Einstein Condensation in a Dimple Trap

We study the formation of a Bose-Einstein condensate via the application of an attractive dimple potential to a trapped Bose gas above its critical temperature. This has been achieved experimentally using a tightly-focused laser to generate an optical dipole potential in the centre of a cigar-shaped magnetic trap. As the depth of the dimple potential is increased, the energy of the ground state decreases, eventually becoming equal to the chemical potential, at which point a condensate begins to form. We compare the results of semi-classical Hartree-Fock theory under the Thomas-Fermi approximation to experimental data for both adiabatic and sudden turn-on of the dimple potential.

12 **B. J. Dalton** (ACQAO SUT)

Heisenberg Limited Bose-Einstein condensate interferometry

Boson-boson interactions generally have negative effects on interferometry using Bose-Einstein condensates. However, an experiment proposed by Dunningham and Burnett [1] aims at utilising these interactions for bosons in a symmetric double well potential to develop a form of Heisenberg limited interferometry based on the Josephson model [2]. Briefly, the bosons are initially in a fragmented condensate and split equally between two modes localised in each well. The inter-well barrier is then lowered so that the evolution is dominated by tunnelling. At a suitable time, the quantum state acquires a well-defined relative phase [3], resulting in a clear interference pattern. At this time the barrier height is raised so that evolution is then dominated by collisions. The clear interference pattern becomes diffuse in a short (collapse) time due to the dephasing effect of collisions. However, after a longer (revival) time a clear interference pattern revives due to rephasing effects. The revival time is measured with an accuracy scaling inversely with the boson number N. The second stage is repeated but now with a slightly asymmetric potential, and the shift in the interference pattern is measured at the revival time. The shift in phase together with the measurement of revival time leads to a determination of the asymmetry parameter with a Heisenberg limited precision. A theoretical treatment of the process in terms of the probability of measuring the relative phase will be presented.

[1] J. Dunningham & K. Burnett, Phys. Rev. A **70**, 033601 (2004).
[2] A. Leggett, Rev. Mod. Phys. **73**, 307 (2001).
[3] D. Pegg & S. Barnett, Phys. Rev. A **42**, 6713 (1990).

13 **B. J. Dalton** (ACQAO SUT)

Theory of Bose-Einstein condensate interferometry

A theory of decoherence and dephasing effects has been developed for BEC interferometry using a phase space method. The density operator is represented by a phase space distribution functional [1], using the Wigner representation for highly occupied condensate modes and the positive P representation for basically unoccupied non-condensate modes [2], [3]. The theory is now generalised to apply to interferometry situations where macroscopic occupancy may occur for up to two condensate modes, such as in double-well BEC interferometry. A mean field theory for treating dephasing effects based on a two-mode approximation [4] has previously been developed, with generalised coupled Gross-Pitaevskii equations determining the mode functions. For the new phase space treatment allowing also for decoherence effects, Ito stochastic equations for condensate and non-condensate fields are obtained from Fokker-Planck equations for the distribution functional. Stochastic averages then give the quantum correlation functions [5] that describe interference experiments.

[1] M. Steel et al, Phys. Rev. A **58**, 4824 (1998).
[2] B. Dalton, J. Phys: Conference Series **67**, 012059 (2007).
[3] S. Hoffmann et al, "Hybrid phase-space simulation method for interacting Bose fields" Accepted, Phys. Rev. A.
[4] B. Dalton, J. Mod. Opt. **54**, 615 (2007).
[5] R. Bach et al, Phys. Rev. A **70**, 063622 (2004).

14 **M. Singh, A. Akulshin, A. Sidorov, R. McLean and P. Hannaford** (ACQAO SUT)

Magnetic Lattice for Ultracold Atoms and BECs on an Atom Chip

Optical lattices produced by the interference of intersecting laser beams are widely used to manipulate and control periodic arrays of ultracold atoms and quantum degenerate gases in a range of fundamental quantum physics experiments, including experiments on low-dimensional quantum gases, the superfluid to Mott insulator quantum phase transition and Anderson localisation. Optical lattices are also finding application as storage registers in quantum information processing.

We are investigating an alternative approach for producing periodic lattices for ultracold atoms based on periodic arrays of magnetic microtraps on an atom chip. We have produced a 1D magnetic lattice of period 10 μm on a magnetic film atom chip based on a grooved TbGdFeCo microstructures. Up to 2 x 10^6 rubidium-87 atoms have been loaded into the magnetic lattice and trapped at less than 5 μm from the chip surface. The measured trap lifetime is currently about 450 ms and radial trap frequencies as high as 90 kHz have been achieved. Future prospects for magnetic lattices will be discussed.

15 **Mandip Singh** (ACQAO SUT)

Macroscopic entanglement between a superconducting loop and Bose Einstein condensate

Entanglement is considered to be one of the most fundamental features of quantum mechanics. In particular, entanglement among macroscopic observables is of prime interest in order to explore how a system behaves at the interface of classical and quantum mechanics. Macroscopically entangled states are also promising candidates for the practical realization of a quantum computer.

In this paper a practically implementable scheme is proposed to generate macroscopic entanglement of a Bose-Einstein condensate in a micro-magnetic trap magnetically coupled to a superconducting loop. The superconducting loop is treated in a quantum superposition of two different flux states coupling with the magnetic trap to generate macroscopic entanglement. The proposal also provides a platform to realise interferometry with an entangled Bose Einstein condensate and to explore physics at the quantum-classical interface.

16 **Gary Ruben** (Monash University)

Vortex-lattice formation and melting in a nonrotating Bose-Einstein condensate.

A vortex-antivortex lattice with honeycomb symmetry has been predicted and observed in numerical models of a nonrotating, pancake-shaped Bose-Einstein condensate (BEC) that is initially segmented into three pieces. The lattice may be contrasted with the well-known hexagonal Abrikosov vortex lattice that forms in rotating BECs. The wave-nature of BEC clouds has previously been tested by allowing two initally separated pieces to collide and observing the resulting Young's interference fringes. If the cloud is instead split into three parts, the resulting pattern changes dramatically into the honeycomb lattice. The lattice creation may be explained in terms of a linear interference process of three expanding wave packets. Magnetic confinement of the BEC subsequently causes the lattice to melt as the vortices interact chaotically, clustering into structures that migrate and scatter throughout the cloud.

17 **Chaohong Lee** (ACQAO ANU)

Dynamical Mechanisms of Symmetry-Breaking Transitions in A Coupled Two-Component Condensate

In this presentation, we will show both mean-field and full quantum dynamics of symmetry-breaking transitions (SBTs) in a coupled two-component Bose-Einstein condensate. By controlling s-wave scattering lengths and coupling strength, it is possible to stimulate SBTs between normal and spontaneously polarized ground states. In static transitions, the probability maxima of full quantum ground states correspond to the mean-field ground states. In dynamical transitions, due to the vanishing of excitation gaps, the mean-field dynamics obeys universal Kibble-Zurek scalings. Both mean-field and full quantum defect modes appear as damped oscillations, but they appear at different critical points and undergo different oscillation regimes. The anomalous breakdown of mean-field dynamics induced by SBTs depends on the transition direction. We also discuss the experimental possibility.

18 **L.J. Byron, S.S. Hodgman, R.G. Dall, and A.G. Truscott** (ACQAO ANU)

Progress on a Metastable Helium-Rubidium Dual Species Magneto-Optical Trap

Multi-species combinations of ultracold atoms are currently promoting intense study, both experimentally and theoretically. Several important areas of focus include; interaction-tuning by photo- and magneto-association, quantum statistical effects, and the production of ultracold molecules.

Previously these experiments have been limited to various alkali atom combinations; we intend to create the first realisation of a Bose Einstein Condensate (BEC) consisting of a ground state alkali species, Rubidium (Rb) and a metastable noble-gas species, metastable Helium (He*). Successful production of a binary BEC consisting of Rb and He* would allow for studies of collisional properties, photoassociative spectroscopy and eventually for an investigation into the production of bound ultracold He*Rb molecules.

The first step towards a Rb-He* BEC is the creation of a dual species Rb-He* Magneto-Opical Trap (MOT). At present the MOT loss rates due to Penning ionization are unknown but expected to be high. As theoretical calculations are extremely difficult, we intend to do the first investigation of these loss rates in a MOT. This is important measurement not only because it is a fundamental parameter in the Rb-He* MOT characterisation but also knowing these loss rates will also allow us to maximise the phase space density leading to an improved Rb-He* BEC.

The Rb-He* MOT will be achieved by modifying the existing He* beam line at the Australian National University to include both He* and Rubidium. We will present current progress towards the creation of a Rb-He* MOT including; Rubidium laser set-up, Rubidium 2D+ MOT source design and characterisation, and the additions and modifications to the existing He* apparatus. As well as this preliminary Rb-He* MOT studies will be presented.

19 **J. Sabbatini and M.J. Davis** (ACQAO UQ)

Topological defects formation and dynamics in ^{87}Rb Bose Ferromagnet with quantum noise

Since the introduction of optical traps we experimented a proliferation of studies involving a new type of Bose-Einstein condensate (BEC) the one with multiple internal spin components, the so called spinor condensates. Optical traps allow multiple internal degrees of freedom, then a new class of symmetries and symmetry-breaking schemes are available to be probed, giving us the access to a wider zoo of topological defects. We study the formation mechanisms and dynamics of topological defects, such domain walls and spin vortices, in a ferromagnetic spin-1 ^{87}Rb BEC embedded in a changing magnetic field. Recently in the experiment of the Berkeley group [1] the spontaneous formation of such topological defects were observed and later studied in several papers as the Saito *et al.* [2] and Gu *et al.* [3]. We focus on the formation of those object due to quantum fluctuations and noise thanks to stochastic methods. The noise source can be both internal, particle exchange between species, or external such as the coupling with the thermal bath. We finally compare our results with both experimental and theoretical works and check consistency with the Kibble-Zurek mechanism, a general approach to topological defects formation in phase transition processes.

[1] L. E. Sadler, J. M. Higbie, S. R. Leslie, M. Vengalattore, and D. M. Stamper-Kurn, Nature (London) **443**, 312 (2006)
[2] H. Saito, Y. Kawaguchi, and M. Ueda, Phys. Rew. A **75**, 013621 (2007)
[3] Q. Gu, and H. Qiu, Phys. Rev. Lett. **98**, 200401 (2007)

20 **S.L. Midgley, S. Wüster, M.K. Olsen, M.J. Davis and K.V. Kheruntsyan** (ACQAO UQ)

A comparative study of simulation methods for the dissociation of molecular Bose-Einstein condensates.

Dissociation of a molecular BEC raises the possibility of studying macroscopic correlations in ensembles of massive particles as it produces entangled atom pairs composed of atoms having equal and opposite momenta in the molecule's rest frame [1]. We describe a pairing mean-field theory related to the Hartree-Fock-Bogoliubov approach, and apply it to the dissociation of a $^{87}Rb_2$ molecular Bose-Einstein condensate (BEC) into correlated bosonic atom pairs. We also perform calculations using stochastic phase-space methods [2], particularly the positive P-representation method and the truncated Wigner method. By comparing the results of the three methods we are able to assess the strength of these theoretical models in describing molecular dissociation. We find that when considering spatially inhomogeneous molecular condensates it is the truncated Wigner method that is most successful in describing molecular dissociation beyond the short time limit. We also calculate atom-atom correlations generated by the dissociation process.

[1] K. V. Kheruntsyan, M. K. Olsen and P. D. Drummond, Phys. Rev. Lett. **95**, 150405 (2005)
[2] C. W. Gardiner and P. Zoller, *Quantum Noise*, 3rd ed. (Springer-Verlag, Berlin Heidelberg, 2004)

21 **P. Dyke, G. Veeravalli, E. Kuhnle, W. Rowlands, P. Hannaford and C. J. Vale** (ACQAO SUT)

Progress towards a quasi-2D gas of fermions

Advances in the control and manipulation of ultracold atoms have opened the way to studies of lower dimensional quantum gases. The behaviour of lower dimensional gases in the quantum degenerate regime can be drastically different from their three dimensional counterparts. A truly 2D gas will not undergo condensation at finite temperatures. However, it was shown by Berezinskii [1] that an interacting gas at sufficiently low temperatures can form a superfluid, which is characterised by the spontaneous formation of bound vortex-antivortex pairs [2]. Recent experiments using ultracold bosonic gases have been able to access this Berezinskii- Kosterlitz- Thouless (BKT) regime in quasi-2D potentials using optical lattices [3], laser light sheets [4,5], and a combination of optical and magnetic trapping [6]. Utilising a single beam optical dipole trap, produced by a Yb:YAG 1075 nm fibre laser focussed into a light sheet [4,5] with cylindrical optics and beam waists of ~5 m in the tight direction and > 300 m in the weak transverse direction to yield an aspect ratio of ~ 60, we will investigate the quasi-2D regime of a strongly interacting Fermi gas of Li^6 atoms.

[1] V. L. Berezinskii, *Sov. Phys. JETP* **34**, 610-616 (1972).
[2] J. M. Kosterlitz and D. J. Thouless, J. Phys. C: Solid State Physics 6, 1181 (1973).
[3] P. Krüger, Z. Hadzibabic, and J. Dalibard, Phys. Rev. Lett. **99**, 040402 (2007).
[4] A. Görlitz *et al*., Phys. Rev. Lett. 87, 130402 (2001).
[5] P. Clade *et al*., cond-mat/08053519 (2008).
[6] N. L. Smith *et al*., J. Phys. B: At. Mol. Opt. Phys. **38**, 223–235 (2005).

22 **A.M. Akulshin, R.J. McLean, A.I. Sidorov and P. Hannaford** (ACQAO SUT)

Low-intensity nonlinear processes in coherent atomic media

The nonlinear susceptibility of atomic media may be significantly enhanced by laser-induced long-lived Zeeman or hyperfine coherences. Potential applications in communication and quantum information processing generate widespread interest in such coherent media. An experimental study of the nonlinear optical properties of atomic media, paying particular attention to spatial nonlinear effects such as light induced wave-guiding, focussing and diffraction is presented.

Under the conditions required for electromagnetically induced transparency and absorption, nonlinear susceptibilities have been measured using a phase heterodyne technique. The high nonlinearity makes efficient four-wave mixing (FWM) easily achievable and the intensity dependence of the new waves provides another measure of Kerr nonlinearity.

Laser-induced atomic coherence may also result in frequency up-conversion [1]. Relatively weak cw infrared radiation may produce collimated and coherent blue light in a dense Rb vapour. Frequency up-conversion due to stimulated FWM has been studied both with a hot Rb vapour and a laser-cooled atomic cloud. It has been found that a wave-guiding effect plays a crucial role in the process. The direction of the blue light satisfies with the momentum conservation for a FWM process.

Dissipative, dispersive and nonlinear properties of coherent atomic media [2] are closely associated and a link between different effects such as light storage, FWM, slow and fast light is discussed.

[1] A.S. Zibrov *et al.,* Phys. Rev. A, **65**, 051801 (2002).
[2] A.M. Akulshin *et al.,* J. Opt. B: Quantum Semiclass. Opt. **5**, S479 (2003).

23 **W.G.A. Brown, R.J. McLean, A.I. Sidorov, P. Hannaford and A.M. Akulshin** (ACQAO SUT)

Negative group velocity in a coherence-free cold atomic medium

We have observed the propagation of a light pulse approximately 35 ns long with a negative group velocity through a laser-cooled ^{85}Rb atomic medium. The anomalous dispersion results from linear atom–light interaction and is unrelated to long-lived ground-state coherences often associated with fast light in atomic media. The observed delay of approximately 3.6 ns for a pulse attenuated by less than 50% corresponds to a negative group velocity ($-c/360$) in the Rb MOT, in good agreement with the dispersion measured independently by an rf heterodyne method. The spectral region of anomalous dispersion is between 15 and 40 MHz, which is intermediate to the Doppler-broadened spectral profiles of a thermal vapour, where the associated dispersion is generally low, and the subnatural linewidth features associated with ground state coherences that are often exploited for fast and slow light experiments, where microsecond pulses are required to match the spectral range of the steep dispersion.

24 **Michał Matuszewski, Tristram J. Alexander, and Yuri S. Kivshar** (ACQAO ANU)

Spin-Domain Formation in Antiferromagnetic Spin-1 Condensates

Antiferromagnetic (polar) condensates are generally believed not to display modulational instability and spin-domain formation. We demonstrate that in the presence of magnetic field antiferromagnetic spin-1 Bose-Einstein condensates can undergo spatial modulational instability, somewhat analogous to polarization modulational instability in nonlinear optics, followed by the subsequent generation of domains. Employing numerical simulations for realistic conditions, we show how this novel effect can be observed in sodium condensates confined in an optical trap.

25 **S.S. Hodgman, L.J. Byron, R.G. Dall, K.G.H. Baldwin, and A.G. Truscott** (ACQAO ANU)

Measuring the Metastable 2 $^3S_1$–1 $^1S_0$ Transition Rate in Helium

Atomic transition rates can be used to test the accuracy of theories such as Quantum electrodynamics (QED). A transition of particular interest is the 2 $^3S_1$–1 $^1S_0$ metastable transition in Helium. Theoretical results place this lifetime around 8000s, however the only experimental measurement to date has a 30% uncertainty [1].

We plan to use magnetically trapped metastable helium to determine the transition rate by measuring UV Photons emitted from He* atoms via an electron multiplier with the appropriate filter. The ratio of 2 $^3S_1$–1 $^1S_0$ to 2 $^3P_1$–1 $^1S_0$ decay rates will be used to determine the 2 $^3S_1$–1 $^1S_0$ decay rate. In a previous measurement we calculated the 2 $^3P_1$–1 $^1S_0$ transition rate to an accuracy of 4 % using this method [2], and similar precision is expected.

[1] H.W. Moos and J. R. Woodworth, Physical Review A **12**, 2455 (1975)
[2] R. G. Dall, K. G. H. Baldwin, L.J. Byron and A.G. Truscott, Physical Review Letters **100**, 023001 (2008).

26 **T. Haigh, A. Ferris, M. Davis, M. Olsen** (ACQAO UQ)

Macroscopic superpositions in small double well condensates

We use a two-mode approximation, and a number state analysis to investigate the behaviour of small condensates in a double well potential. Double well condensates have a rich ground state structure, which can include both number squeezed states and coherent superposition states, depending on the ratio of (attractive or repulsive) interactions to the tunnel coupling between the wells. It may be possible to dynamically create a macroscopic superposition state by making use of the Feshbach resonance of the condensate atoms[1]. We consider various methods of detecting superposition states. We also include uncertainties in the total atom number in the condensate to see what effect this may have on the generation and detection of superposition states.

1. Y. P. Huang and M. G. Moore, Phys. Rev. A **73**, 023606 (2006).

27 **E.D. van Ooijen, S. Haine, M.J. Davis, N.H. Heckenberg, H. Rubinsztein-Dunlop, R. Meppelink, S.B. Koller, J.M. Vogels, P. van der Straten** (University of Queensland)

Shock Waves in a Bose-Einstein Condensate

We observe the formation of shock waves in a Bose-Einstein Condensate [1] containing a large number of sodium atoms. The shock wave is initiated with a repulsive, blue-detuned light barrier, intersecting the BEC, after which two shock fronts appear. We observe breakdown of these waves when the size of these waves approaches the healing length of the condensate. Here, the wave front splits into two parts and clear fringes appear. The experiment is modelled using the 3D Gross-Pitaevskii equation and gives excellent qualitative agreement. In these experiments, no significant heating or particle loss is observed, confirming the dispersive character of this phenomenon.

[1] M.A. Hoefer, M.J. Ablowitz, I. Coddington, E.A. Cornell, P. Engels, and V. Schweikhard, Phys. Rev. A **74** 023623 (2006)

28 **Dave Kielpinski** (Griffith University)

Toward laser-cooled hydrogen

The spectroscopy of hydrogen offers opportunities for precision measurement of fundamental constants and high-accuracy tests of physical laws. While standard laser cooling techniques have improved spectroscopic precision in the alkalis by orders of magnitude, they are inapplicable to hydrogen because of the vacuum ultraviolet (121 nm) wavelength of the hydrogen 1S-2P transition. We are currently working to implement a novel laser cooling scheme based on excitation of the two-photon 1S-2S transition by a mode-locked pulse train. The high nonlinear conversion efficiency of mode-locked laser light should enable generation of >1 W average power at the 243 nm cooling wavelength, leading to scattering rates on the order of kHz. To maximise the interaction time of the H atoms with the cooling light, we will guide our cryogenic H beam along the cooling laser beam using a dipole trap at the "magic wavelength" of 515 nm. The cooled, trapped H atoms will provide an excellent starting point for realisation of hydrogen BEC and for a lattice atomic clock. A successful demonstration of our scheme will enable laser cooling of the antihydrogen produced at CERN, leading to an ultra-precise test of CPT symmetry.

Quantum-Atom Optics beyond Bells: short program

Time	Tuesday 25 November
18.00-19.00	Workshop reception

<table>
<tr><th>Time</th><th>Wednesday 26 November</th><th>Thursday 27 November</th><th>Friday 28 November</th></tr>
<tr><td>8.30-10.30</td><td>Chair: Bachor
Ertmer (30 min)
Drummond (30)
Brand (30)
Helmerson (30)</td><td>Chair: Hannaford
Corney (30)
Hu (30)
Schreck (30)
Vale (30)</td><td>Chair: Dalton
Orozco (30)
Carmichael (30)
Parkins (30)
Luiten (30)</td></tr>
<tr><td>10.30-11.00</td><td colspan="3">Coffee break</td></tr>
<tr><td>11.00-13.10.</td><td>Chair: Savage
Blakie (30)
B. Anderson (30)
Davis (30)
Mottenen (20)
Sykes (20)</td><td>Chair: Kheruntsyan
Petrov (30)
Mark (30)
Martin (30)
Ticknor (20)
Liu (20)</td><td>Chair: Akulshin
Janousek (30)
Buchler (30)
White (20)
O'Brien (20)
Poldy (20)</td></tr>
<tr><td>13.10-14.10</td><td colspan="3">Lunch</td></tr>
<tr><td>14.10-15.30</td><td>Orozco lecture 1</td><td rowspan="2">Chair: Baldwin
Hope (30)
Close (30)
Debs (20)
Truscott (30)</td><td>Orozco lecture 3</td></tr>
<tr><td>15.30-16.00</td><td>Coffee break</td><td>Coffee break</td></tr>
<tr><td>16.00-16.30</td><td rowspan="3">Chair: Sidorov
Oberthaler (30)
Hall (30)
R. Anderson (20)
Steinberg (20)
Muller (20)</td><td>Coffee/CI meeting</td><td rowspan="3">Chair: McLean
Hoogerland (30)
Alexander (30)
Turner (20)
Bradley (20)
Haine (20)</td></tr>
<tr><td>16.30-17.30</td><td>CI meeting/Orozco lecture 2</td></tr>
<tr><td>17.30-1800</td><td>CI meeting</td></tr>
<tr><td>18.00-19.00</td><td rowspan="2">Dinner (own arrangements)</td><td></td><td></td></tr>
<tr><td>19.00-20.00</td><td rowspan="2">Workshop dinner</td><td></td></tr>
<tr><td>20.00-21.30</td><td>Posters (leave up)</td><td></td></tr>
</table>