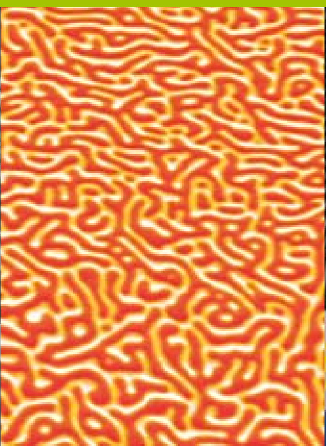

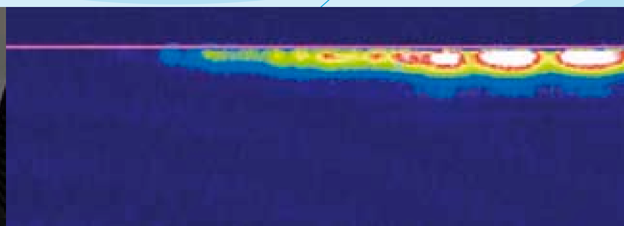

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report for the year 2006

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THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY OF QUEENSLAND
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CONTENTS

FOREWORD

Quantum-Atom Optics continues to thrive as an innovative and expanding research field and the investment in our Centre is starting to pay off. Many of our ambitious research projects are now producing results that are attracting international attention and are represented in the leading journals. We have had many successes both in the theory teams and the experimental projects. We are particularly pleased to report that the Australian Research Council (ARC) has recognised the outstanding quality of our people and of our work and will continue to fund the Centre until 2011. This gives us the opportunity to make even greater and longer-lasting research contributions.

The ARC Centre of Excellence for Quantum-Atom Optics (ACQAO) is a key part of Australia's participation in the rapid development of quantum science and technology that is happening around the world. We concentrate on fundamental science questions and create the scientific tools for the engineers of the future, with a focus on the application of quantum and wave properties of light and atoms. We work together with other Centres and teams in Australia, our partners in Europe, the USA and New Zealand to set the foundations for a diverse range of quantum technologies in areas such as sensing, communication and data processing.

Our strength is that we are able to investigate the quantum behaviour of larger objects, involving thousands or even millions of atoms, and observe the transition from the microscopic quantum world of a few particles to the macroscopic classical world. Technology has advanced, even in the last five years and in many industrial situations very small objects and structures, on a micron or nano scale and involving only thousands or hundreds of atoms, are now regularly used for state-of-the-art devices. To understand and control the quantum properties of these objects is a key step on the path to developing even more powerful devices. In parallel is the intellectual challenge to be able to understand, describe and use the interface between the microscopic and the macroscopic world, then to develop new theory models and to quantitatively test them.

ACQAO has a unique combination of scientists with expertise in both the quantum properties of light and the generation and use of Bose-Einstein condensates (BECs), a quantum system involving thousands to millions of atoms. ACQAO combines leading scientists in Australia in this field working in three cities, at The Australian National University (ANU) in Canberra, at the University of Queensland (UQ) in Brisbane and at Swinburne University of Technology (SUT) in Melbourne. Throughout the previous four years, strong collaborations and exchanges have developed within the Centre and with our international partners. This has demonstrated how effective such a virtual Centre can be and has ensured that Australian contributions to quantum and atom optics are now widely recognised internationally.

Highlights of our progress in 2006 include the investigation of an atom laser beam in Rb and He*, the optical trapping of utlracold 6 Li atoms, theory of quantum-atom optics using the dissociation of a molecular BEC, spin polarised superfluid fermi gases, quantum and classical field simulations of a BEC, self trapped structures and localisation of a BEC in optical lattices, quantum dynamics of polarisation squeezing, experimental studies of the information delay in slow light, development of superbly quiet squeezed light at Rb wavelengths and the demonstration of the tools for spatial quantum optics and the invention of nonlinear optical spatial mode conversion techniques.

Our Centre is part of the vision of the ARC to promote excellence in the most successful fields of research and to give select teams the opportunity to be major players in the international arena.

ACQAO is particularly active in its collaborations with Europe and New Zealand. Our scientific workshops are valued highly with an increasing number of students and staff choosing to work with us for extended periods.

The great interest in wanting to work with ACQAO in Australia is a good measure of the recognition of our work.

This is all made possible by the generous support of the ARC, through direct funding and fellowships, from the three Universities (ANU, UQ, SUT), the State Government of Queensland and the Defence Science & Technology Organisation (DSTO).

Through this we can tackle ambitious research projects in parallel, create an intensive collaboration of staff and students, provide opportunities for young scientists and raise the awareness of the wider community in the beauty and the importance of quantum science and technology.

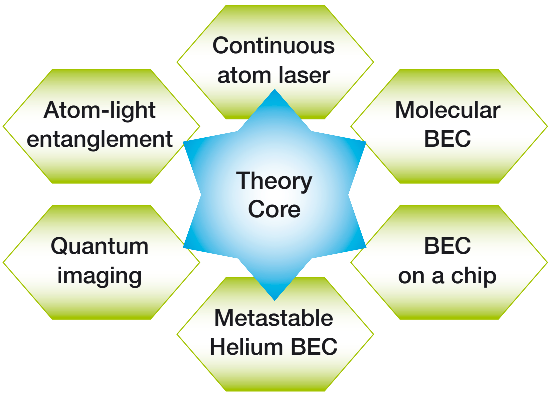
This report describes the research highlights and in detail describes the structure of our Centre, the staff and students, our research plans and our achievements in 2006.

You can learn from our science summaries, in the middle of this report, the technical details and the advances of our theory teams and experimental projects.

I hope this report stimulates you to learn more about the exciting venture of creating quantum technologies for the future.

Professor Hans-A. Bachor
Research Director

QUANTUM-ATOM OPTICS



Our research goals

In optics we consider the propagation and effects of light in the form of electro-magnetic waves. Interference fringes are a typical result in this type of classical optics. In contrast quantum optics adds the effects based on the quantisation, or particle nature, of light to this.

It has become easier over the years to isolate such quantum effects of light and they appear more frequently as a limit in the quality or sensitivity of optical instruments. In addition, quantum optics offers new possibilities for the communication of information with light. The field of photonics, which uses the laser as the source of coherent light and is until now essentially based on classical optics, will benefit soon from the advances in quantum optics.

Australia has established a strong international research profile in quantum optics, both through pioneering theory work as well as state of the art experiments.

We normally consider atoms as particles, that can be detected one at a time and interacting via collisions in a gas, or by being close to each other in a liquid or solid. However, atoms also have wavelike properties; they can be described by quantum mechanical wave functions and the interference between the probability amplitudes.

We are now in the position to build atom lasers which produce coherent matter waves and we will soon be able to study the quantum statistical properties of atoms in a way similar to optics. This opens the way for new examples of quantum technology, such as improved sensors based on atom interferometry. In ACQAO we are combining and developing the links between quantum optics and atom optics.

Entanglement

Entanglement is one of the key concepts of quantum physics. It describes the properties of two systems, which originate from one source, and are, in the ideal case, indistinguishable. For example, these could be two laser beams, propagating in different directions created in one source and which contain identical information, modulation and noise. Or they could be two, or more, beams of particles which have identical properties. Some of the pioneering theory work on entanglement was done in Australia and the extension to systems of many particles (page 26) is one of the goals of our theory teams in ACQAO.

The ANU researchers have already built optical sources that produce strong entanglement. Within ACQAO, we will use this light to demonstrate spatial effects, such as the positioning of a laser beam, the measurement of small displacements and the communication of spatial information. We now have optimised these techniques and report measurements better than the conventional quantum limit (page 24). We also have developed new techniques to predict exactly the complexity of real experiments (page 22).

Entanglement between individual atoms has been studied in detail and we are now asking the question how we can describe and generate entanglement between many particles. We are developing new tools to make these effects visible. Groups of atoms can be manipulated, cooled, stopped and trapped until they reach such a low temperature that the wave and quantum effects dominate. Theory has shown some years ago that the deBroglie waves of the atoms can be made to overlap. The Bosonic atoms such as ^{87}Rb, ^{133}Cs, ^{4}He then make a rapid transition into a new state of matter once they cool below a critical temperature.

This is the so-called Bose-Einstein Condensate (BEC) that has properties vastly different from a cloud of atoms and we have developed techniques to study the details of this transition (page 14).

Recent years have seen a very rapid development of the concepts and experiments with fermions. Fermionic atoms can combine into bosonic molecules and can be cooled to form BECs. They can dissociate, and in well controlled situations this can lead to quantum correlations of individual atoms. We are carrying out pioneering theoretical work (page 30) and are expanding our experimental capabilities in the new area of fermionic quantum-atom optics.

Different BECs for new science

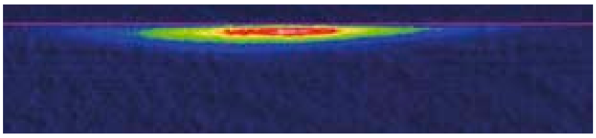
By the end of 2006, Australia had five BECs, four in Rb and one in metastable Helium, all optimised for different studies and applications. Four BECs are part of ACQAO and are used to further develop the technology, to make the apparatus more reliable and the parameters better controlled.

The apparatus at SUT is based on unique technology within the Centre which uses permanent magnets with micron-sized structure to guide, trap and condense the atoms (page 17). This allows us to reduce the size and complexity of the apparatus. The SUT technology will allow us to build small, reliable BEC instruments which can be developed into robust and very sensitive sensors, based on atom interferometry.

Alternatively we can use it to probe the magnetic field above the chip surface with unprecedented accuracy. We can now generate multiple BECs on the chip that allow us to study the interference of matter waves in great detail.

The metastable He* BEC at the ANU is very stable and reproducible (page 16) and allows us to investigate the properties of the BEC using detectors sensitive to single atoms. This will be used to investigate the statistical nature of the BEC and to probe deeper into the quantum properties of this atomic system.

We are also extending the generation of a BEC from atoms to molecules. Based on successful experiments in Europe and the USA on generating and Bose-condensing molecules we are building an apparatus for ^{6}Li fermions and can already trap the atoms and locate them in focused optical beams (page 31). This will allow us to demonstrate novel correlation effects, predicted in theories created by members of our Centre.



Fragmentation of Rb BEC close to a surface

Atom Laser and transferring entanglement

It is one more step from the BEC to the atom laser, a device that produces a coherent beam of atoms. In 2006 we demonstrated the operation of an atom laser with He* (page 16). With the Rubidium apparatus we are developing new techniques that will improve the quality of the laser beam, the beam intensity and the beam shape to thus turn it into a practical device for precision experiments in analogy with the development of the optical lasers in the 1960s and 70s. On the experimental side we have now built an optimised BEC that produces larger atom numbers and has better controlled parameters (page 11).

This Centre combines, in a unique way, quantum optics and atom optics, theory and experiments. We have developed a clear vision and detailed plans for a novel apparatus that converts quantum correlations from an optical laser beam into quantum correlations in the atom laser beams.

This ambitious project will bring together many of our experimental skills such as generating non classical light (page 24), design of atom lasers and single atom detection, as well as detailed model calculations (page 13).

In parallel we are investigating ways of transferring quantum correlations from light to atoms and vice versa as an initial step in designing atomic storage for optical quantum information. During 2006 we studied the delay of information using slow light in Rb vapours and investigated the additional noise introduced by the atoms (page 23).

Related experiments on quantum information, communication and cryptography are making rapid progress and are carried out independently of ACQAO at the ANU and in collaboration with other Centres of Excellence.

Theory points the way

All these experimental goals are explained and frequently initiated by a very strong theory core at UQ and ANU, which combines the expertise of world-renowned researchers. The different techniques and expertise from quantum optics, field theory and non-linear optics are combined within one powerful group of scientists who guide and support the experimental work. In some cases the theory is well ahead of the experiments.

One example are new ideas and techniques developed at UQ to simulate the properties of fermions from first principles (page 37) which will lead to experiments at SUT. Another first is the exact theory of atom correlations in low dimensions (page 20) that has recently been tested by other groups in the world.

New results, such as the theory of the quantum properties of optical lattices and periodic structures and the formation of 3D solitons in coupled atomic-molecular BECs (page 34), can lead us to future experiments.

Scientific Tools for the Future

The goal of the Centre is to provide the scientific tools required to develop quantum and atom optics into a whole new field of optical quantum technology. These include ideas, experimental demonstrations and simulations. This work over the next five years prepares the way for applied work in quantum technology in 10–15 years.

The Centre does this by combining the separate concepts of quantum and atom optics, by linking the leading scientists in Australia and by developing an exchange with our partners in Europe and New Zealand, who are in some of the most productive groups in this field. In this way the Centre is contributing to the international research effort and ensures that future optical quantum technology will be developed in and remain accessible to Australia.

THE NODES — STRUCTURE OF THE CENTRE

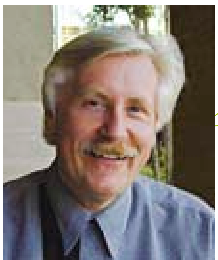
The Centre combines many of the leading scientists in quantum and atom optics in Australia. They are thriving in three locations: Canberra, Melbourne and Brisbane, and are linked through joint scientific projects, the sharing of expertise and equipment and the exchange of people. We have formed research teams spanning several nodes. The scientific goals have been chosen to be ambitious. These are moving forward the present frontiers of knowledge in quantum and atom optics by employing the expertise of all members of the Centre.

The Centre is coordinated from the Australian National University (ANU) by the Research Director, Hans-A. Bachor and the Chief Operations Officer (COO), Ruth Wilson. The science is carried out by a theory core group and six experimental projects. At the end of 2006 we have a total staff of 49 plus 45 postgraduate students.

Ruth Wilson

Back row L to R: Thomas Argue, Simon Haine, Matt Jeppesen, Cristina Figl, John Close
Front row L to R: Mattias Johnsson, Joe Hope, Julien Dugue, Nick Robins

ANU FAC, Canberra



Hans-A. Bachor

At the ANU we have the research node which carries out experimental work with the Rb BEC and atom laser, including the development of new nondestructive diagnostic techniques (John Close, Nick Robins, Cristina Figl). This node also undertakes experiments on quantum imaging, spatial entanglement (Hans-A. Bachor, Charles Harb, Ping Koy Lam) and tunable entangled light and experiments showing the transfer of quantum correlation from light to atoms and the storage of quantum correlations (Ben Buchler, Oliver Gloeckl, Ping Koy Lam). This is complemented by innovative theory (Joe Hope, Craig Savage, Mattias Johnsson) that concentrates on the properties of coherent atom sources, quantum feedback, atom light entanglement and correlated atom lasers.

Q-Imaging team L to R: Katherine Wagner, Hongxin Zou, Charles Harb, Vincent Delaubert, Jiri Janousek, Roger Senior, Ping Koy Lam, Hans-A. Bachor

Oliver Gloeckl in the Atom Light Entanglement Laboratory

ANU IAS, Canberra

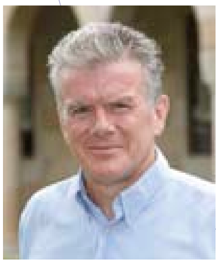
Ken Baldwin

On the other side of the ANU campus, in the Institute of Advanced Studies (IAS) and located within the Research School of Physical Sciences and Engineering, we have a node that combines theory and experiments. The laboratory now has a very reliable He* BEC experiment to study quantum statistical effects in BECs through single atom detection (Andrew Truscott, Robert Dall and Ken Baldwin, who is Node Director and Centre Deputy Director). The theoretical group has world leading experience in non-linear optics, optical lattices and soliton physics (Yuri Kivshar, Tristram Alexander, Chaohong Lee, Elena Ostrovskaya) and their focus is on the properties of matter waves in optical lattices and other periodic structures.

AIS team (clockwise from bottom centre): Betaa Dabrowska, Tristram Alexander, Chaohong Lee, Wendy Quinn, Deborah Bordeaux, Elena Ostrovskaya, Robert Dall, Ken Baldwin, Andrew Truscott, Lesa Byron (Yuri Kivshar absent)

Yuri Kivshar, Elena Ostrovskaya, Andrei Sidorov, Ken Baldwin at CI meeting in Brisbane

UNIVERSITY OF QUEENSLAND, Brisbane

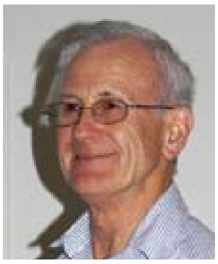


Peter Drummond

At the University of Queensland (UQ) we have a node located in the School of Physical Sciences that is led by pioneering theorists (Peter Drummond — Node Director, Ashton Bradley, Joel Corney, Matthew Davis, Karen Kheruntsyan, Murray Olsen, Hui Hu, Xia-Ji Liu, and Margaret Reid). Their work includes the numerical and quantum phase-space methods for the simulation of BECs, cold molecule formation, quantum correlations in low dimensional Bose and Fermi gases, fundamental tests of quantum mechanics, and the development of specialized software. The theory work connects to many aspects of the experimental projects in all the other nodes.

Back row L to R: Kalai Kumar Rajagopal, Murray Olsen, Eric Cavalcanti, Margaret Reid
Middle row L to R: John Hedditch, Peter Drummond, Scott Hoffmann, Geoffrey Lee, Stephane Golding
Front row L to R: Paul Schwenn, Clinton Roy, Joel Corney, David Barry, Karen Kheruntsyan, Ashton Bradley, Aurelien Perrin

SWINBURNE UNIVERSITY OF TECHNOLOGY, Melbourne



Peter Hannaford

At Swinburne University of Technology (SUT), the Centre has two experimental projects and laboratories located in the Faculty of Engineering and Industrial Sciences with Peter Hannaford as Node Director. SUT has pioneered the use of micro-fabricated permanent magnet structures as part of a unique Rb BEC on a chip experiment (Brenton Hall, Peter Hannaford, Russell McLean, Andrei Sidorov).

Shannon Whitlock, Brenton Hall, Peter Hannaford, Russell Anderson, Andrei Sidorov

In parallel, an experiment for the generation and condensation of Lithium-6 molecules is in progress (Grainne Duffy, Peter Hannaford, Wayne Rowlands). A small theory group complements this work (Bryan Dalton, Tien Kieu).

Mandip Singh and Michael Volk working on the BEC magnetic lattice experiment

Back row L to R: Mandip Singh, Russell McLean, Andrei Sidorov, Peter Hannaford, Bryan Dalton, Tatiana Tchernova, Chris Ticknor, Shannon Whitlock, Brenton Hall, James Wang, Michael Volk, Paul Dyke
Front row L to R: Grainne Duffy, Gopisankararao Veeravalli, Saeed Ghanbari, Wayne Rowlands, Jurgen Fuchs

In addition to the personnel mentioned here, the Centre includes a number of research fellows, postdoctoral fellows, graduate students and visiting fellows, listed on page 54. The administration includes research assistant Max Colla (ANU FAC) and Administrators Linda Schumacher/Stephanie Golding (UQ), Tatiana Tchernova (SUT) and Deborah Bordeau/Wendy Quinn (ANU IAS).

GOVERNANCE

While the Research Director, Hans-A. Bachor, is responsible for the overall science direction and performance, the Chief Operations Officer, Ruth Wilson, is responsible for all operational and financial aspects of the Centre.

The fundamental decisions for the Centre are determined by all Chief Investigators which is achieved during bi-annual CI meetings (Brisbane May 2006, Brisbane December 2006). The ongoing administration is supervised by the Executive Committee, which meets four times a year. Node Directors are responsible for the continuous operation of the four nodes. Regular science meetings were held fortnightly within the nodes. Planning sessions were held in Canberra in preparation for the ARC Review of our Centre held in September.

The daily administrative work is carried out by the COO and the administrative assistants at SUT, UQ and the IAS. The financial status and science progress are reported to the COO and Research Director on a quarterly basis via the Node Directors.

Centre Management Meetings 2006			
CI meeting	All CIs & COO	Bi-annual	12 April, Melbourne 2 May, Brisbane 6 December, Brisbane
Executive Board	Res Dir. & COO Node Directors	Quarterly	9 March, video 20 June, video 30 August, video
Advisory Board	International & national members	Annually	14 February, Canberra
International Workshop	Centre & partners, other AUS groups	Bi-annual	10 February, Kioloa 4 December, Brisbane
Individual Project & group	Staff & students, visitors	Fortnightly	
IP committee	Node directors, Universities	Annually	6 April, phone conference

Advisory Board

We are fortunate to have an Advisory Board of outstanding expertise. Our international science advisors are respected leaders in the field and highly distinguished scientists as listed; they are:

Prof Alain Aspect, Institut d'Optique, Orsay France

Prof Keith Burnett, Oxford University, United Kingdom

Prof William Phillips, Nobel Laureate, NIST Maryland, USA

Prof Eugene Polzik, Niels Bohr Institute Copenhagen, Denmark

Prof David Pegg, Griffith University Brisbane, Australia.

Our national board members who provide expertise in liasing with the Australian public and potential end-users of our research are:

Senator Gary Humphries
Bob McMullan MP
Steven Duvall, Intel
Dr Bruce Whan SUT
David Wilson DSTO

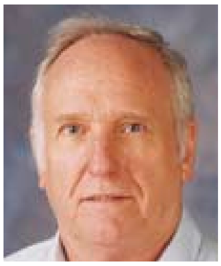
Advisory Board members

Professor Alain Aspect

Professor Keith Burnett

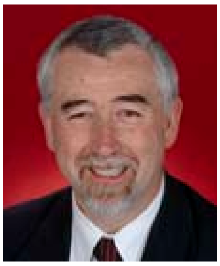
Professor William Phillips

Professor Eugene Polzik



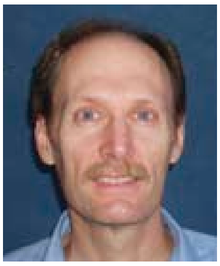
Professor David Pegg

National Board members



Senator Gary Humphries

Bob McMullan MP



Steven Duvall

Dr Bruce Whan

David Wilson

Studies of the Continuous Raman atom laser

J. Dugue, C. Figl, M. Jeppesen, P. Summers, N. P Robins and J. D. Close,
ACQAO, Department of Physics,
Australian National University, Australia.

From the start of the Centre we have been concentrating on developing the atom laser as a useful tool for future precision measurement applications and investigations in fundamental physics. We have studied the classical aspects of the atom laser, investigating the limits to flux and the presence of classical fluctuations on the atom laser beam [1, 2]. In 2006, we demonstrated a new type of continuous atom laser which we showed to be capable of producing a dramatically higher output flux with substantially improved beam quality [3]. Critically, this type of atom laser is based on a coherent two photon Raman transition, which transfers a highly directed momentum kick to the output-coupled atoms [4].

Our current experiments are aimed at measuring in detail how the momentum kick affects the output flux and classical fluctuations of a continuous atom laser. Such a study requires a careful calibration of the outcoupling strength given by the two photon optical Rabi frequency, which mediates the transfer of atoms from the trapped condensate to the untrapped atom laser beam. We will use a technique developed in our group that involves fitting experimental Rabi-cycling data (see figure) directly to a highly accurate 3D numerical simulation of the experiment with no free parameters, typically reducing the measurement errors to around the 5% level.

In addition to improving the quality and flux of an atom laser the two photon Raman output-coupler allows the possibility modify the quantum noise properties of the atom laser beam. For precision measurement applications and fundamental investigations in physics, it is important to explore the possibility of squeezing the noise on an atom laser below the standard quantum limit. ACQAO theorists Simon Haine, Joe Hope, Murray Olsen and Mattias Johnsson have proposed a series of experiments on squeezed and entangled atom lasers [5, 6]. They predict that replacing one of the Raman beams with a squeezed light beam may allow a transfer of squeezing from the light to the atoms, paving the way for future experiments in quantum atom optics. We intend to implement such a system, in collaboration with the Atom Light Entanglement team.

Figure 1. Experimental data showing Rabi cycling between the magnetic hyperfine states of the $5^2\mathrm{S}_{\frac{1}{2}}\mathrm{F} = 2$ manifold of $^{87}\mathrm{Rb}$. For each individual data set a $50\,\mu s$ pulse of Raman coupling is applied to a trapped BEC, followed by a free evolution time of 5 ms and absorption imaging. The images show the BEC atoms coherently Rabi cycling between the separately resolved magnetic sub-states as we increase the laser power in the Raman pulse.

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Apparatus to create a pumped atom laser

M. Jeppesen, C. Figl, J. Dugue, P. Summers, N. P Robins and J. D. Close,
ACQAO, Department of Physics,
Australian National University, Australia.

One of the primary goals of ACQAO is to produce and study a pumped atom laser. All existing atom laser systems are only capable of pulsed operation – being analogous to an optical laser in which the power has been turned off, so that the output beam quickly drains the source. Many of the highly valued properties of an optical laser are only achieved through sustained continuous operation, and this is also thought to be the case for the atom laser. This project aims to take a step beyond the current generation of atom lasers, by replenishing the source of the atom laser – a Bose-Einstein condensate – from a reservoir of thermal atoms, while at the same time outcoupling atoms to produce an atom laser beam. We will attempt to make a rate equation study of the relative population in the condensate, atom laser beam and thermal reservoir. Our calculations indicate that only very large condensates (consisting of at least one million atoms) will provide a sufficient signal-to-noise ratio to observe pumping effects in this experiment.

To this end, we have constructed a specialised apparatus for pumping a large ^{87}Rb BEC. In the figure below, we show a schematic of the machine which consists of: a 2D-Magneto-Optical Trap (MOT) pre-cooling and loading stage (1), a large volume 3D-MOT (2) in ultra high vacuum (UHV) for capture and loading of the magnetic trap (3), followed by magnetic transport to a specialised, ultra-stable trap for evaporative cooling and atom laser production. At present we produce pure condensates of 5×10^5 atoms in the $|1, -1\rangle$ ground state while simultaneously producing pure condensates of 10^5 atoms in the $|2, 2\rangle$ state via sympathetic cooling [1]. The fraction of atoms in each state can be controlled precisely to produce any mixture of the two, from pure $|1, -1\rangle$ to pure $|2, 2\rangle$. Such a system provides an excellent starting point for experiments aimed at pumping a BEC, either by using evaporative cooling or spontaneous decay [2, 3].

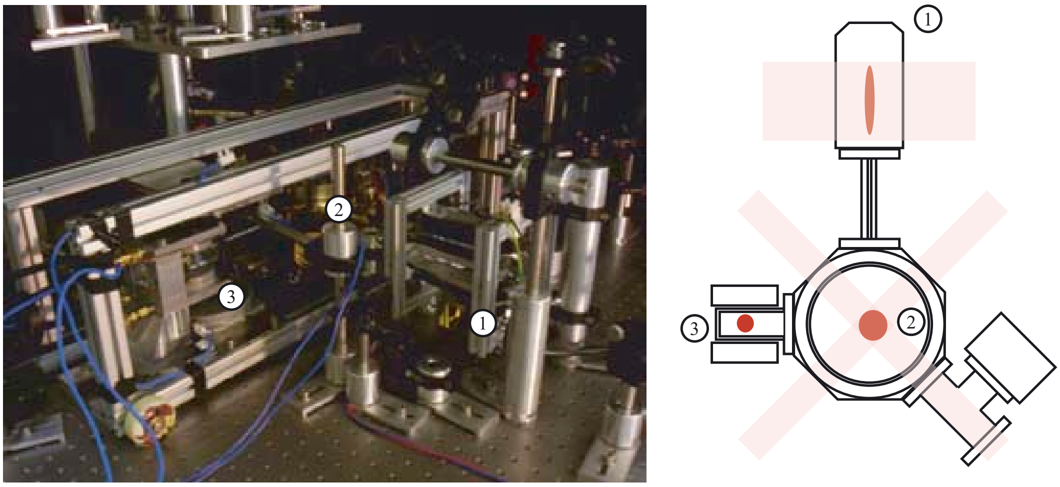

Figure 1: Image and Schematic drawing of the new atom laser machine, showing the 2D-MOT (1), UHV 3D-MOT (2), and UHV QUIC trap (3).

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Measuring and Manipulating the Quantum Statistics of an Atom Laser

A. S. Bradley and M. K. Olsen
ACQAO, School of Physical Sciences, University of Queensland, Australia
S. A. Haine and J. J. Hope
ACQAO, Faculty of Science, Australian National University, Australia

The ability to measure and manipulate the quantum state of an optical laser has allowed for the testing of some fundamental aspects of quantum mechanics, such as Bell's inequality, the Einstein-Podolsky-Rosen paradox, and quantum teleportation, for the first time. This theoretical research focusses on manipulating the quantum state of an atom laser beam. We have previously shown that by using a Raman transition to outcouple an atom laser in certain parameter regimes, the quantum state of one of the beams can be transferred to the propagating atom laser beam. By using nonclassical light to outcouple, we have shown that this can lead to squeezed [1] and entangled [2] atom laser beams. We have recently extended this work and shown that, in the case of squeezed light being used to outcouple, that entanglement can be generated between the transmitted light and the outcoupled atoms [3]. Such entanglement could be used as a tool for entangling spatially separated condensates, and increasing the sensitivity of an atom-light interferometer to below the standard quantum limit.

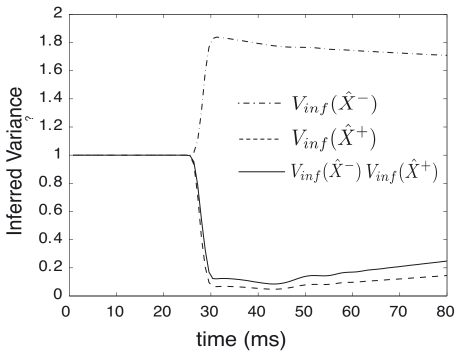

Figure 1: Entanglement between the transmitted optical beam and the atom laser beam. The quadratures of the atom laser beam can be inferred to well below the quantum limit by measuring the optical beam.

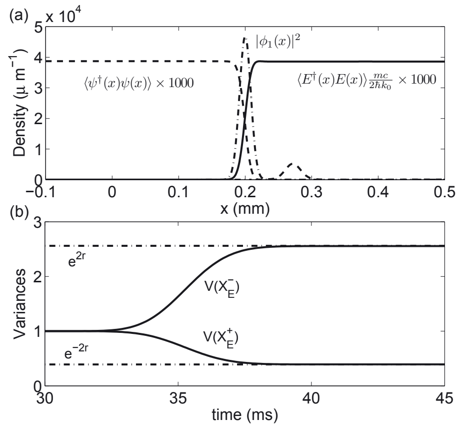

Figure 2: (a) A squeezed atomic beam is coupled into the condensate. (b) Variance of the quadratures of the emitted optical field.

Measurement of the quantum state of a matterwave field via homodyne detection is much more difficult than for an optical field. This is due to the difficulty in mode matching the output to a local oscillator with a well defined phase, and the challenges involved in efficient atom detection. We have developed a scheme for measuring the quadrature statistics of an atom laser beam using existing optical homodyning and Raman atom laser techniques. Reversal of the normal Raman atom laser outcoupling scheme is used to map the quantum statistics of an incoupled beam to an optical probe beam. A multimode model of the spatial propagation dynamics shows that the Raman incoupler gives a clear signal of de Broglie wave quadrature squeezing for both pulsed and continuous inputs. We have shown that experimental realisations of the scheme may be tested with existing methods via measurements of Glauber's intensity correlation function [4]. Finally, by combining the incoupling and outcoupling schemes may provide a method of teleporting atomic pulses.

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3D Bose-Einstein condensates from first principles

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In this research topic, we focus on first-principles calculations (both numerical and analytical) of the many-body quantum dynamics of BEC. The numerical work includes 3D dynamical simulations of colliding condensates and of the formation of BEC via the evaporative cooling process. Inspired by the completely quantum-mechanical regimes predicted by the simulations, the analytic work includes the formulation of the robust, generalised BEC criteria, and calculations of the fundamental noise limits on the centre-of-mass degrees of freedom. The numerical simulations are performed by means of the $+P$ stochastic phase-space method, which can be applied to a range of cold-atom systems, sometimes involving over $10^{1,000,000}$ quantum states.

Firstly, we simulate[1] the quantum dynamics of macroscopic colliding Bose-Einstein condensates[3] with 150,000 interacting atoms. Measurable two-body correlations[2] and velocity distributions are found for experimentally accessible parameters and evolution times. Preliminary experimental measurements from Aspect's group (Orsay) with He* agree qualitatively with the theoretical predictions.

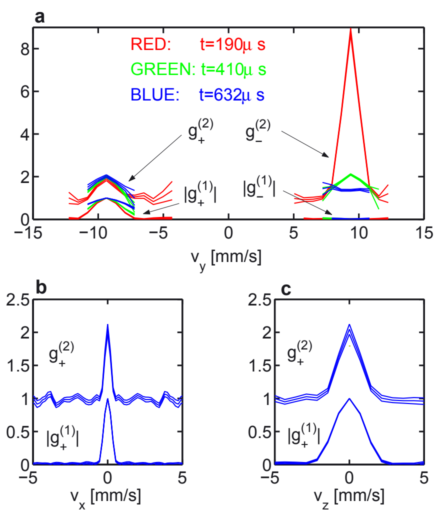

Figure: Correlations between scattered atoms for parameters corresponding to a sodium BEC in a cigar-shaped trap similar to the MIT experiment[3], but at lower densities. Correlations $g^{(1)}$ (coherence) and $g^{(2)}$ (density correlations) shown are in velocity space between a point on the shell of scattered atoms (where $v_y = -9.37\text{mm/s}$, and $v_x = v_z = 0$) and the second velocity shown along the horizontal axis. Top panel **a** – correlations in a direction perpendicular to the collision direction and radial with respect to the shell of scattered atoms; panel **b** correlations along the collision direction; panel **c** correlations perpendicular to the collision direction but tangential to the scattered shell. Details in [1]. Triple lines are 1σ error bars.

Secondly, we simulate the formation of BEC via evaporative cooling[4], to extend earlier predictions[5] of residual centre-of-mass oscillations. Statistical uncertainty in the phase of the oscillations causes the atoms to spontaneously condense into different single-particle states in each realisation. In this situation, the Penrose-Onsager criterion for BEC fails to predict presence of the condensate. Thus, we are evaluating various higher-order correlation functions as alternative criteria for condensation.

Finally, we have calculated [6] the fundamental limits that quantum noise places on the accuracy of mean position (centre of mass) measurements for small low-temperature bosonic and fermionic systems. We have identified a standard quantum limit for such measurements and show that this limit can be exceeded by diffusion of the centre of mass wavepacket.

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One-dimensional Bose gases

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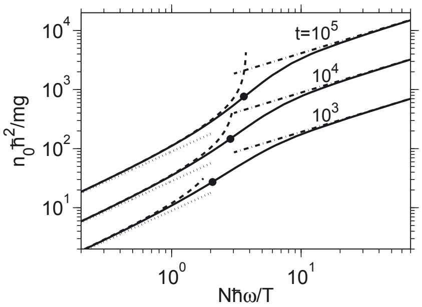
The one-dimensional (1D) Bose-gas model of particles interacting via a delta-function potential is of fundamental importance to quantum many-body physics. The model is exactly solvable for arbitrary interactions and temperatures, and it is now experimentally realizable with ultra-cold alkali atoms in highly anisotropic trapping potentials. This means there are unique opportunities for accurate tests of theory that were previously unavailable. In 2006 we have made further progress in our highly successful stream of theoretical studies of 1D Bose gases [1].

1. We have studied the nature of the transition to a coherent state in a harmonically trapped repulsive 1D Bose gas in the weakly interacting regime [2]. We have found a parameter space where the transition can be identified as an *interaction-induced* crossover to a quasi-condensate, which is present in both a finite-size system and in the thermodynamic limit. We predict that this scenario occurs at the crossover atom number $N_{\rm co} = (T/3\hbar\omega)\ln(\hbar^2 T/mg^2)$ or the crossover temperature $T_{\rm co} = 3N\hbar\omega/\ln(N\hbar^3\omega/mg^2)$. Here, ω is the trap frequency, $g > 0$ is the 1D coupling, N is the total atom number, and T is the temperature (in energy units). The interaction-induced crossover is contrasted to Bose-Einstein condensation in a harmonically trapped *ideal* gas, which occurs as a pure *finite-size* effect (absent in the thermodynamic limit) at a critical number $N_C = T/(\hbar\omega)\ln(2T/\hbar\omega)$.



The figure shows the peak density n_0 (in units of $mg/\hbar^2$) of a harmonically trapped 1D Bose gas versus $N\hbar\omega/T$ for three values of $t = 2\hbar^2 T/mg^2$ [2]. The three black dots show the crossover atom number $N_{\rm co}\hbar\omega/T$ for each t. The numerical results (solid line) obtained using the exact uniform solutions and the local density approximation are compared with the behavior in the quasi-condensate regime (dash-dotted lines), with the ideal Bose gas result (dashed lines), and the classical Boltzmann gas (dotted lines).

2. We have analyzed the thermodynamic properties of an array of independent 1D Bose gases in a 2D optical lattice. In particular, we have calculated the total entropy of the system and compared it with the respective result for the 3D BEC [3]. The objective is to analyze how the temperature of the system is altered upon an adiabatic (entropy preserving) transfer of the 3D gas into 1D tubes. Our results can be applied to the recent experimental measurements of the local pair correlation in Weiss's group [4], which can potentially include finite temperature effects with no fitting parameters. We propose that the 1D pair correlation measurements can be used as a new method of thermometry.

3. For the 1D gas with attractive interactions we have solved the Lieb-Liniger equations for the exact many-body wave functions for up to 20 particles. This system exhibits a symmetry-breaking quantum phase transition to a localised soliton [5], and the exact energy eigenvalues were previously unknown. This work is being prepared for publication, and in the future we intend to calculate the correlation functions and study the dynamics of a sweep across the critical point.

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Experiments with a metastable condensate

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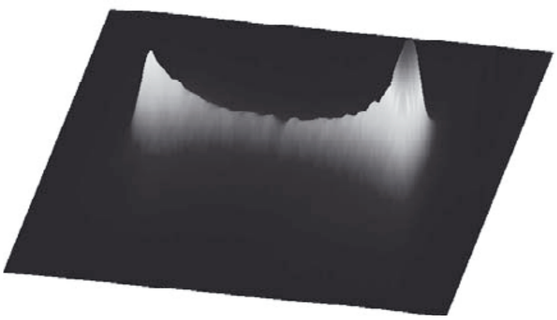
The main goal of our research is to study the evolution of relative phase between two Bose Einstein condensates (BEC). To probe condensate relative phase our group aims to build a double well metastable helium (He*) BEC. He* can be readily detected atom by atom, by virtue of the 20 eV energy stored in the 2^3S_1 excited state [1]. He* atoms will be condensed into both wells, and atoms will then be output coupled onto a micro-channel plate (MCP) detector. The statistics of the arrival times and positions of these atoms can be analysed to yield phase information of the two condensates. Theorists [2] predict that the "build-up" of relative phase should be seen after a measurement of only $\sim$ 50 atoms, making such an experiment extremely difficult with alkali BEC's for which efficient single atom detection is virtually impossible.

In December 2005 we were able to condense He* for the first time in our laboratory [3]. Typically we reach the transition temperature for BEC with around ten million atoms. Recently, we have created a metastable atom laser by using radio frequency (RF) output coupling to create a matter wave beam from our condensate. In previous demonstrations of atom laser beams much heavier atoms than helium have been used. In such case the minimum of the trapping potential is displaced substantially by gravity relative to the minimum of the magnetic field. As a result output coupling occurs on planar surfaces rather than ellipsoid surfaces, which is the case for He*. Despite this added complexity, we have been able to demonstrate that our atom laser is coherent by output coupling with two RF frequencies and observing interference fringes in the atom laser output.

We have also imaged the transverse profile of the atom laser beam using a micro-channel plate and phosphor screen detector located about 4 cm below our condensate. The output beam is only well collimated and approximately Gaussian if the atoms are outcoupled from the very bottom of the BEC. If the atoms are coupled out near the centre of the condensate they experience a repulsive force from the atoms in the BEC, resulting in large lensing and the appearance of caustics on the edge of the beam. Fig. 1 shows an image of our atom laser beam outcoupled from the centre of the BEC.



In the coming year we plan to study the properties of our atom laser further. In particular, we would like to measure the linewidth of the matter wave beam. Moreover, by creating two condensates and RF outcoupling from the system we will measure the build of relative phase between two BEC's.

Figure 1: Image of an atom laser beam outcoupled from the centre of the BEC. Note the appearance of caustics at the edge of the beam. The size of the image is 1 cm $\times$ 1.3 cm.

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Origin of a disordered potential on a magnetic film atom chip

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We report [1] on the origin of fragmentation of ultracold atomic clouds observed recently on a magnetic film atom chip [2]. One half of the chip is coated with a TbGdFeCo magnetic film and the other half has only gold coating. Rubidium atoms are confined in a highly elongated trapping potential produced by the edge of the magnetic film and a bias magnetic field. We observed that when the atomic cloud expands axially in the trapping potential, is moved close to the surface of the magnetic film and is evaporatively cooled with RF radiation, the atomic density profile becomes fragmented (Fig. 1a). Ultracold atoms with temperatures close to quantum degeneracy have a narrow energy distribution and thus concentrate in local minima of the potential. An atomic cloud positioned below the non-magnetic gold film does not exhibit oscillating density variations (Fig. 1c) indicating a smooth potential in the axial direction. Using spatially resolved radio frequency spectroscopy we have measured small spatial variations of the magnetic field.

We have developed a model which quantitatively describes how two-dimensional variations in the perpendicular magnetization lead to the appearance of random magnetic fields. Inhomogeneity in the film magnetization produces a spatially varying magnetic field component parallel to the edge that corrugates the bottom of the trapping potential. Using a standard approach incorporating a two-dimensional Fourier transform of the random magnetization and the magnetic scalar potential we have derived a general expression for the axial component B_z of the disordered magnetic field [1]. In the case of white noise fluctuations we obtained an analytic expression for $< B_z >_{rms}$ which accurately describes the magnetic disorder potential below magnetic and non-magnetic areas of the chip. The expression predicts that the corrugated magnetic component decays with a y^{-2} dependence below the magnetic film edge which is in good agreement with our experimental observations of a $y^{-1.8\pm0.3}$ dependence.

Our model can be applied to any particular pattern of atom optical elements made from magnetic films and will be used for optimizing the performance of magnetic films on atom chips.

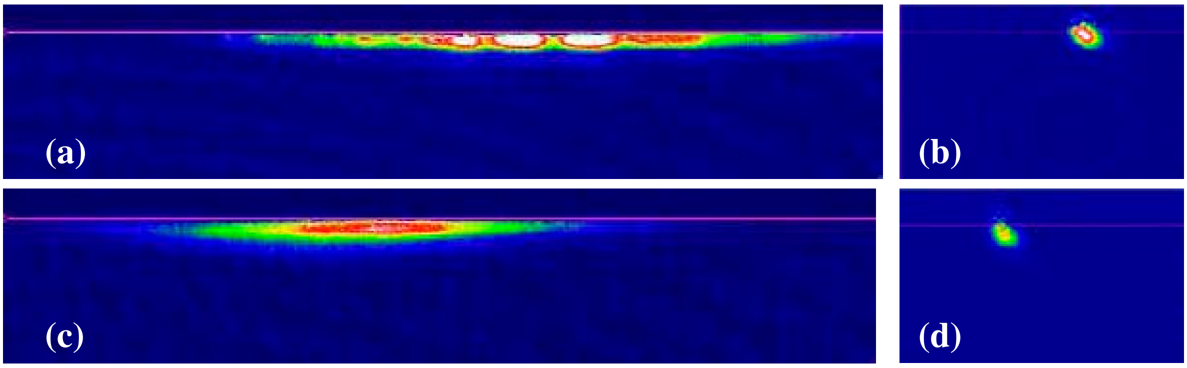

Figure 1. Absorption images of the atomic cloud positioned 50 μm below the TbGdFeCo film in the axial (a) and radial (b) directions and 50 μm below the gold film in the axial (c) and radial (d) directions. Fragmentation of the cloud in the axial direction is clearly visible below the magnetic film.

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Condensate splitting in an asymmetric double well

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As a consequence of their extremely low energy scale and superfluid nature, Bose-Einstein condensates show excellent promise in their development as probes for precision measurement of near-surface potentials [1, 2]. We report on experiments which utilize the quantum nature of the condensate to investigate dynamic splitting in a double well with tunable asymmetry onboard a magnetic film atom chip (Fig 1). We show that the distribution of atoms between the two wells responds strongly to the asymmetry and that a tilt sensor for measuring gravity fields can be realised with a single shot sensitivity of δg/g $\approx 2\times10^{-4}$ [3]. In addition we propose a simple model that allows the sensitivity of the double well sensor to be evaluated (Fig 2a). This shows good agreement with the experimental measurements (Fig 2b) and allows the motivation of additional improvements for the future development of this non interferometric technique (Fig 2c).

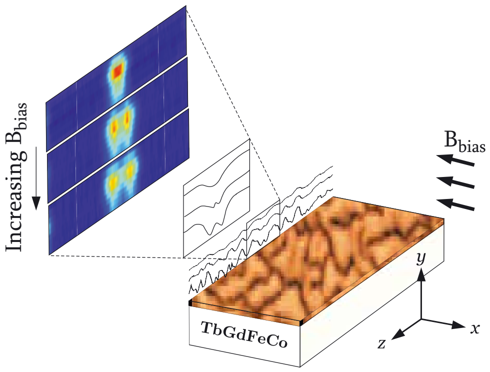

Fig. 1. Schematic showing the corrugated potential above the edge of the TbGdFeCo magnetic film. Located around z=0 is a double well potential that can be used to dynamically split a BEC through the transformation of a single well into a double well by increasing B_{bias}. The number of atoms in each well are observed by using absorption imaging after 2 ms time of flight (processed images on left). The corrugated potential is due to the presence of a small amount of magnetic inhomogeneity in the film

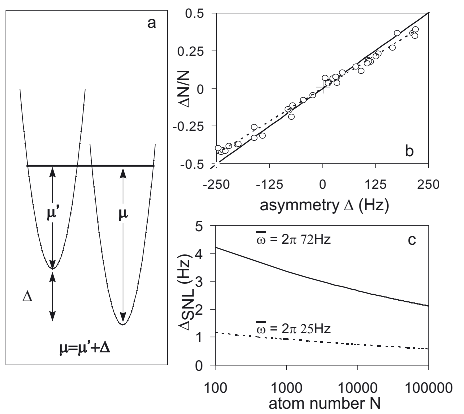

Fig. 2. (a) The asymmetric double well is represented by two identical harmonic traps offset by Δ with a ground state distribution obeying $\mu = \mu' + \Delta$. From this model we can extract the dependence of the fractional number difference $(N_R - N_L)/(N_L + N_R)$ on Δ,where N represents the number of atoms in either right or left wells. (b) Adiabatic splitting of a condensate in the presence of a constant asymmetry shows the fractional number difference (circles) in good agreement with the proposed theory (solid line). (c) Our model indicates that the shot noise limited sensitivity depends weakly on atom number and is proportional to the geometric mean of the trap frequencies.

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Quantum simulations of Bose-Einstein condensates.

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This project considers situations in which beyond mean-field effects are important in the dynamics of Bose gases even at zero temperature. Typically we make use of the the truncated Wigner method for solving the quantum evolution of a Bose-condensed gas [1]. The inclusion of initial quantum noise means the technique can represent quantum corrections to the classical field equations of motion.

We have studied the effect of quantum and thermal fluctuations in the well-known "Bosenova" experiment [2], where the scattering length a ^{85}Rb BEC was switched to negative values for controlled periods using a Feshbach resonance, and the time evolution of the condensate studied. While GPE studies incorporating three body recombination have qualitatively agreed with the experimental results, there is a lack of quantitative agreement [3]. We found that although there were some differences from the GPE treatment, there were not sufficient to describe the experimental data [4].

Motivated by an experiment performed by the Otago group, we have studied the loading of a BEC into the band edge of a 1D optical lattice plus magnetic trap. Interactions cause a rapid loss of coherence and thermalisation in the Rabi cycling between momentum states that is observed, and we have quantitatively modelled this with results in reasonable quantitative agreement with the data. A paper written with the Otago group is currently being finalised.

The process of degenerate four-wave mixing of a BEC in a moving 1D optical lattice has also been studied, where atoms from a mother condensate form two entangled daughter condensates with differing momenta. A simplified three-mode model showed that significant continuous variable entanglement could be generated [5], and current works aims to determine whether this persists in more detailed 1D calculations. We have also developed a proposal for and experimental scheme to measure atomic quadratures and prove such entanglement.

We have been simulating the loading of a trapped BEC into an optical lattice which is then accelerated towards the band edge, similar to the experiments performed by De Sarlo *et al.* [6]. We have shown that quantum fluctuations determine the time scale for dynamical instability leading to the formation of soliton trains at random positions and a thermal component. We have also shown that phase-imprinting can fix the locations of the trains [7].

Recent analytic work has suggested that quantum fluctuations in BECs in an infinite system can cause a non-zero drag force on an object in a flow at all velocities [8], in contradiction with our conventional understanding of superfluidity . We have recently begun calculations aimed at conclusively demonstrating this force in a finite system.

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Classical field simulations of thermal Bose-Einstein condensates

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The aim of this project is to continue to develop and apply methods for describing the dynamics of Bose-Einstein condensates at finite temperature. The techniques being utilised are approximate; however they are aimed at performing non-perturbative calculations for realistic experimental systems. The project is directly relevant to the atom-laser project at ANU, and potentially useful for the He^* and atom-chip BEC projects within ACQAO. It is mainly based at UQ with collaborators at the University of Otago.

The computational techniqued has become known as the classical field approximation, where the Gross-Pitaevskii equation (GPE) is used as a model of highly occupied interacting atomic modes [1]. In 2006 Blakie, Bradley, Davis and Gardiner were invited to submit a paper on this topic to the condensed matter review journal Advances in Physics, and this should be complete in early 2007.

The first application of the method to an experimental system has been to investigate the shift in the critical temperature T_c of condensation for the experiment of Gerbier *et al.* [2]. We find that critical fluctuations result in a significant increase of T_c as compared to a full Hartree-Fock-Bogoliubov (HFB) treatment, however both calculations lie within the experimental error bars [3].

Two-dimensional systems have been a major focus for 2006. Classical field methods are particularly useful for low-dimensional systems that have a more slowly increasing density of states. Recently, phase defects in quasi-2D condensates have been reported [4], and this was followed with a measurement of the first-order correlation function that provides evidence for a superfluid Berezinskii-Kosterlitz-Thouless (BKT) phase [5]. We have been studying the penetration of vortices into the centre of a trapped 2D condensate, analysing the experimental technique of determing the behaviour of the first-order coherence function, and considering the measurement of scissor mode properties for establishing the presence and nature of superfluidity in the system.

We have continued work on the formation of a vortex lattice during rotating Bose-Einstein condensation using a stochastic Gross-Pitaevskii equation for the highly-occupied modes coupled to a quenched rotating thermal cloud. This work is nearing submission for publication.

We have recently begun work on a 1D model of a continuously pumped atom laser using classical field methods, where the condensate is continuously replenished from a thermal atomic reservoir using a realistic growth scenario. The project focuses on the properties of the output beam and will provide realistic estimates of the linewidth and coherence limitations of a cw atom laser.

Using kinetic theory rather than classical field theory we have modelled the formation of a elongated condensate in a temperature quench as realised by the Orsay group [6]. We intend to carry out more appropriate classical field calculations that should provide improved agreement with experiment.

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Role of adiabatic evolution in a double-well atom interferometer

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We consider the evolution of a single-atom wavefunction in a time-dependent double-well interferometer in the presence of a spatially variable asymmetric potential. We examine the case where a single trapping potential is dynamically split into a double well and then recombined again. The interferometer involves a measurement of the first excited state population as a sensitive measure of the asymmetric potential. It can be viewed as a quantum-state Mach-Zehnder interferometer where the evolution of the quantum state of an atom via the two separated wells is analogous to the propagation of an optical field via two paths. Based on a two-mode approximation a simple Bloch vector model provides an adequate description of the splitting-holding-recombination sequence and takes into account the presence of asymmetry at all stages of the interferometric process [1].

We find that the probability P_1 of finding the atom in the excited state at the end of the process is only dependent on the x-component of the Bloch vector. For short splitting and recombination periods non-adiabatic following of the Bloch vector occurs, and then during the holding period the Bloch vector precesses about the torque vector, giving rise to a periodic dependence of the final excited state population on the holding time (see Fig. 1a), which may be used to measure the value of the asymmetric potential. In the case of a slow splitting process (splitting time equal to 200 times the vibrational period) the fringe amplitude is significantly reduced (Fig.1b). The reduced fringing is attributed to the onset of adiabatic following during the splitting stage. In the Mach-Zehnder model it can be seen as the unbalanced distribution of the wavefunction between two wells (optical paths) which in turn leads to a reduction in the measured signal. A full numerical solution of the multi-state Schrödinger equation reveals the break-down of the two-mode Bloch vector model at very short splitting times indicating the existence of an optimal range of splitting times [1].

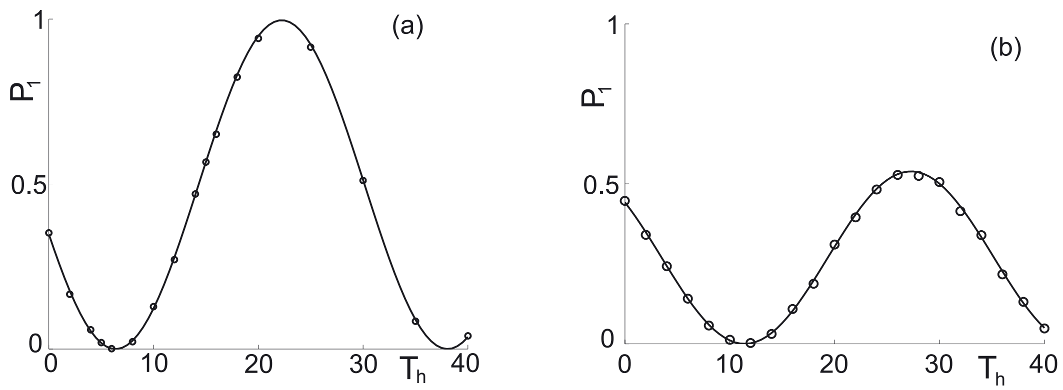

Figure 1. Dependence of the first excited state population P_1 on the duration of the holding stage T_h for various splitting and recombination stages with T_s = T_r = 20 (a), 200 (b). Results of the Bloch vector model are represented by solid lines and those of the full numerical simulations are presented by circles. T_s, T_r and T_h are in units of the vibrational frequency of the original potential well.

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Quantum dynamics of polarisation squeezing in optical fibres

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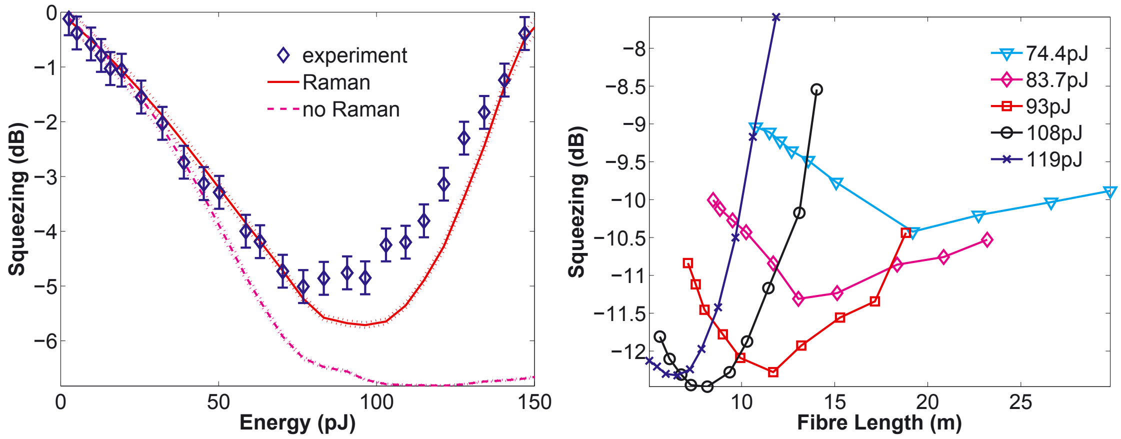
Polarisation squeezing in optical fibres is an efficient means of producing highly squeezed light[1]. Because the experiments operate in a very nonclassical regime, the results are very sensitive to additional nonlinear and thermal effects in the fibre. To quantitatively characterise such experiments, we perform first-principles, quantum dynamical simulations of intense, ultrashort pulses in a fibre, including all significant quantum and thermal noise. We compare simulation and experiments to find excellent agreement over a wide range of pulse energies and fibre lengths[2]. From the simulations, we can identify the particular noise sources that are the limiting factors at high and low input energy.

In the experiment, two equal-intensity pulses propagate along orthogonal polarisation axes of a polarisa maintaining fibre, emerging simultaneously with a $\frac{\pi}{2}$ phase difference. The squeezed pulses are combined on a half-wave plate and the squeezing is measured at a frequency of $17.5\mathrm{MHz}$, to avoid technical noise. Most of the excess noise induced by the fibre is common-mode and is thus cancelled.

We use a quantum model that includes the electronic $\chi^{(3)}$ nonlinear responses of the material and nonresonant coupling to phonons in the silica. The phonons provide a non-Markovian reservoir that generates additional, delayed nonlinearity, as well as spontaneous and thermal noise. The coupling is based on the experimentally determined Raman gain $\alpha^R(\omega)$. The simulations are performed with a truncated Wigner technique[3], which provides an accurate simulation of the quantum dynamics for short propagation times and large photon number. The quantum effects enter via initial vacuum noise, which makes the technique ideally suited to squeezing calculations.



Left: Comparison of simulations and experiment for $L = 13.35\mathrm{m}$. Dashed line is the simulation with a fully electronic nonlinearity (i.e. no Raman effects). **Right**: Predicted optimum squeezing for various fibre lengths. Parameters: $t_0 = 74\mathrm{fs}$, $z_0 = 0.52\mathrm{m}$, $\overline{n} = 2 \times 10^8$, $E_s = 54\mathrm{pJ}$, $\lambda_0 = 1.51\mu\mathrm{m}$, linear losses 20%.

The figures illustrate the importance of Raman effects. The level of squeezing at first increases with input energy, as expected from the Kerr effect. However, at high intensity, Raman effects degrade the squeezing, leading to an optimum energy for maximum squeezing. This optimum energy is larger for shorter fibre lengths. The simulations predict that the best squeezing will be obtained for at $L = 7$m, where the optimum energy equals the soliton energy.

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Information delay via electromagnetically induced transparency

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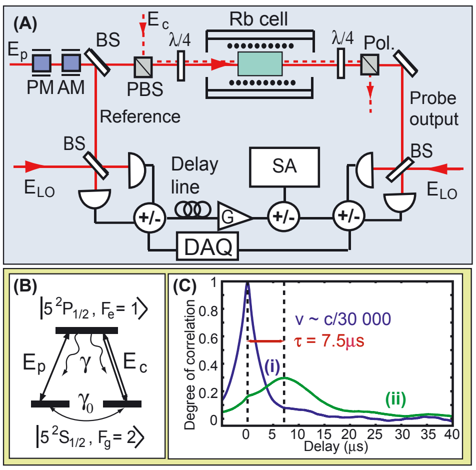
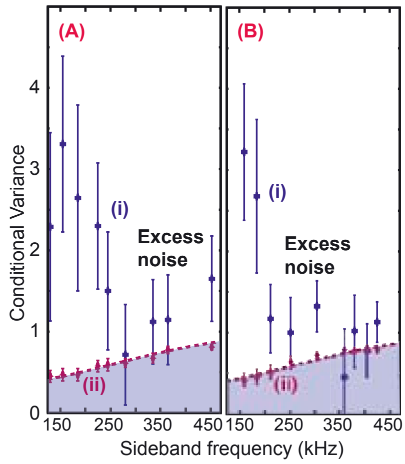
Following theoretical proposals [1], electromagnetically induced transparency (EIT) has become the subject of much interest for controlled atomic storage of quantum states of light. One experiment [2] has even shown an EIT transmission of a squeezed state in a vapour cell. Our work has been aimed at quantifying the quantum performance of EIT induced delay using the D1 Rubidium line at 795 nm. EIT delay is typically quantified by measuring the delay of pulses. In our continuous wave system, we applied a noise modulation to our probe beam and then measured the time correlation functions for the probe input and output signals. We obtained a maximum delay of 7.5 μs. Theoretical quantum treatments of EIT delay and storage have suggested no excess noise is added to the delayed light [3]. Since much EIT work is motivated by quantum information processing, we evaluate the performance of EIT delay using well established criteria for continuous variable quantum state measurement - the conditional variance and signal transfer coefficient. To the best of our knowledge, these are the first such measurements of EIT delay. Our conditional variance measurements (right-hand figure below) demonstrate large amounts of excess noise in both the amplitude and phase quadratures of the delayed light [4]. This finding indicates that current theoretical models are incomplete and more work is required to understand the origin of the excess noise.



(A) Experimental schematic. (B) Atomic level scheme used in the experiment. (C) Correlation plots showing a 7.5 μs delay of a noise modulation (bandwidth 60 kHz) between the input (i) and output (ii).



Conditional variance in the (A) amplitude and (B) phase quadratures. The data point groups show (i) EIT and (ii) passive loss conditional variance. The passive loss benchmark was simulated by using a variable beamsplitter to match the EIT transmission

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Squeezed light at 795 nm using periodically poled KTP

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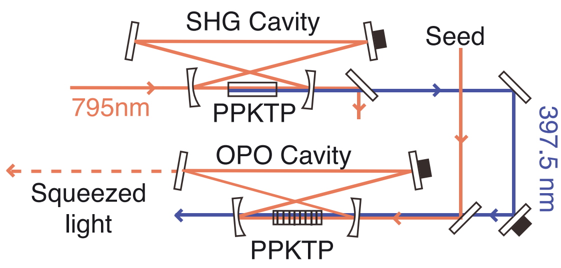
Some quantum information protocols require delay or storage of quantum light states so that the timing of the transaction can be controlled. One potential method for the delay and storage of quantum light states is to engineer a coherent interaction with an atomic level scheme, such as electromagnetically induced transparency [1] or addressing of coherent spin states of atomic ensembles [2]. Before such experiments can be attempted, one requires a source of quantum light states at a compatible atomic wavelength.

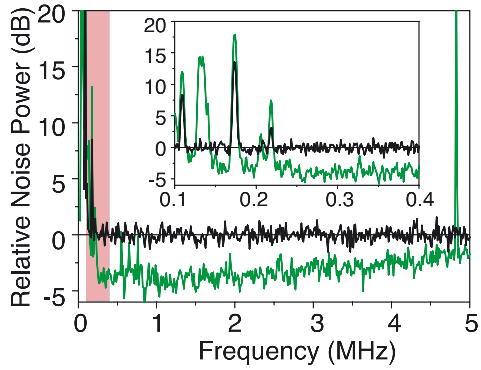
In this experiment we use periodically poled potassium titanyl phosphate (PPKTP) as the nonlinear crystal in an optical parametric oscillator (OPO) for the generation of squeezed light on the D1 line of rubidium which lies at 795 nm. Although OPOs have long been used as sources of squeezed light, the shorter wavelengths required for atomic interactions have always been a challenge due to a limited choice of nonlinear crystals. PPKTP is a new material that has recently been shown to be highly effective over a very wide range of optical frequencies [3].

Our OPO is pumped with a source of blue light generated by a second harmonic generator (SHG) that was also based on a PPKTP crystal. This cavity had a maximum blue output power of 150 mW at 300 mW red input power. Under these conditions the PPKTP was found to suffer grey-traking damage. In order to avoid crystal damage, the blue output power was reduced to 50 mW. In later tests, it was found that better SHG stability was achieved by using an LBO crystal instead of PPKTP.

Locking of the OPO cavity was achieved by injecting a weak 795 nm beam (not shown) in the backwards direction around the ring cavity. This beam did not interact with the squeezing generation of the cavity. The output of the OPO was detected using a balanced homodyne detection system. This detection could be locked to a particular quadrature phase provided the seed beam was strong enough to provided an error signal. The locked results are shown in right-hand figure below, which demonstrate about 5dB of quantum noise suppression [4].



Experimental schematic. The SHG is pumped by a Ti:Sapphire laser at 795nm to generate light at 397.5 nm. This is used as the pump for the OPO cavity that generates squeezed light.



Squeezing measurements from 0 to 5 MHz show a maximum of about 5dB quantum noise suppression. The inset shows a zoom in on the region up to 0.4 MHz

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Quantum information

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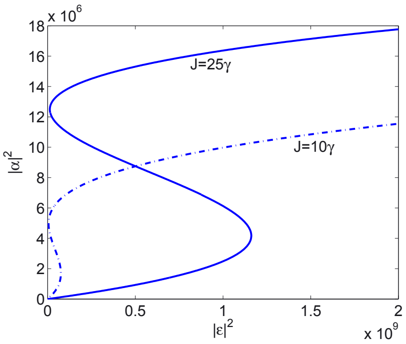
This research studies continuous variable entanglement and states which exhibit the Einstein-Podolsky-Rosen (EPR) paradox, both central to quantum mechanics [1]. This year we have placed special emphasis on investigating the utility of different entanglement criteria, in both the bipartite and tripartite situations, and have developed two three-mode versions of the Einstein-Podolsky-Rosen paradox. The first investigation analysed the degree of violation of certain inequalities in three mode systems using twinned nonlinearities, both concurrent and cascaded, in the cavity and travelling wave configurations [2]. The second investigation extended previous work on evanescently coupled optical parametric oscillators to consider the above threshhold regime, finding that a good degree of bipartite entanglement and violations of the EPR inequalities was available with bright optical outputs [3]. A further investigation analysed the entanglement properties of two evanescently coupled Kerr nonlinear materials inside a Fabry-Perot cavity [4]. This was also found to provide entangled outputs and may be experimentally simpler due to the absence of the phase-matching requirements of $\chi^{(2)}$ media, and could possibly be achieved with optical fibres and commercially available components. Both of these coupled systems provide spatially separated entangled modes, which means that they do not have to be separated by optical devices before measurements can be made, avoiding a possible source of loss.



The nonlinear coupler analysed in Ref. [4] also exhibits bistable behaviour. Here we show the output intensity as a function of pump intensity, for an interaction strength of $\chi = 10^{-6}$, cavity loss rates of $\gamma = 1$ and at resonance, with $\Delta = 0$, and two different values of the coupling, J, as a function of the cavity loss rate. In this symmetric configuration, both inputs and both outputs are equal. The ability to tune both halves of the device separately gives access to a large region of behaviour whose quantum properties await further investigation.

We also rigorously proved that three-mode generalisations of the EPR paradox provide inequalities whose violation is sufficient to demonstrate the presence of full tripartite entanglement, without any conditions as to whether the states involved have Gaussian statistics [5]. These inequalities were used to examine systems with triple $\chi^{(2)}$ nonlinearities, in an extension of previous work [6]. The final project was an intensive investigation of the applicability and utility of several different tripartite entanglement criteria to an experimental scheme which is under investigation in Italy [7]. For this asymmetric scheme, which is a combination of down conversion and sum-frequency generation, we found that it was crucial to choose the appropriate quantum correlations to be measured, with some of the standard inequalities not being violated even though quantum entanglement was demonstrably present.

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Macroscopic superpositions, entanglement and the EPR Paradox

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The aim of this project is to provide strategies for detecting mesoscopic/macroscopic quantum superpositions and Einstein-Podolsky-Rosen paradoxes in mixed states that accurately represent the output of physical systems used to generate squeezing and entanglement. The paradox of macroscopic entanglement occurs where we have a quantum superposition of two macroscopically distinguishable states. A paradox arises because the system cannot be interpreted as being in one state or the other, prior to measurement. This is a fundamental scientific question in both quantum and atom optics, and the experimental groups in the ACQAO Centre are competitively placed to investigate these issues, with world-class squeezing and entanglement.

Experiments in quantum optics are at the forefront in experimentally confirming quantum entanglement. These involve measurements performed on fields generated by parametric amplification, which can have macroscopic output intensities. An article summarising the criteria used to detect the entanglement of the EPR paradox has been published [1] and a review incorporating experimental achievement has been written by invitation and submitted to Reviews of Modern Physics[2]. As part of this review, the criteria have been extended to incorporate Bohm's spin version of the EPR paradox. We have conducted an analysis that reveals the detection efficiencies required if this version of the paradox is to be realised. Closely linked with this work is the effort to propose a feasible experimental arrangement for the violation of Bell inequalities for continuous variable measurements. The quantum theory of such experiments predicts a decoherence-insensitive amplification of the quantum superpositions to enable an interesting version[3] of a Schrodinger cat paradox. Other work in this area includes the relationship between entanglement and fundamental conservations laws and symmetries in quantum electrodynamics [4], as well as work on methods to violate new types of multipartite Bell inequalities.

The challenge to generate and detect *macroscopic* quantum superpositions and entanglement still remains. We have derived criteria[5] for the detection of mesoscopic/macroscopic quantum superpositions that are based on the measurable variances of output probability distributions. To do this, we define the concept of the generalised S-scopic superposition. The criteria are applicable to both discrete and continuous variable measurements, and to entangled states that are of current interest experimentally, namely the squeezed state and the higher-spin and atomic squeezed states. We have shown how these new signatures would allow a macroscopic version of the Einstein-Podolsky-Rosen paradox and a Schrdinger's cat paradox, by enabling confirmation of failure of certain macroscopic quantum mixtures[6]. More recently, we have pointed out that the measure of squeezing of fluctuations in an observable will imply a minimum quantum indeterminacy in the complementary observable, so that large detected squeezing in a particle's momentum is confirmation that the particle's position cannot be thought of as constrained to any microscopic region, prior to measurement. Currently, this work is being extended to a proposal for a macroscopic EPR experiment.

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Encoding and detecting spatial multimode quantum information

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Laser beams are widely used to send quantum information. In our experiment we employ CW beams and squeezed light as the medium to carry information in the form of modulation. Once this can be encoded and detected with a signal to noise ratio better than given by the conventional quantum, or shot noise limit we have the opportunity to consider the use of quantum information protocols.

This technology of using the amplitude and phase quadrature of the light is fairly advanced, has been developed over a long period and many advances have been made to create entangled CW lasers of higher and higher quality [1]. Our interest, in collaboration with our partners at the University of Paris VI and the Danish Technical University in Copenhagen has been to use the spatial properties of the light to encode several orthogonal channels of information. We have shown that the Hermite-Gauss modes with TEM_{00} as the fundamental mode and the TEM_{nj} as the higher order modes in the *x* and *y* directions can all contain independent infrmation that corresponds to a modulation of the spatial properties of light. For example the real and imaginary parts of TEM_{01} correspond to the displacement and tilt of the TEM_{00} reference beam. TEM_{02} corresponds to the size and position of the waist along the *z*-axis.

During 2006 we have demonstrated that we can synthesise such complex beams, that we can produce squeezed light selectively in the required modes and quadratures. We have shown how we can combine the squeezed modes with the reference beam with minimum losses. We have demonstrated that we can build the optimum detector, in the form of a spatial homodyne detector. In our present experiment we can combine all these building blocks to one complete apparatus that allows us to transfer and process multi-mode quantum information. Fig. 1 gives and example of such a system [2]

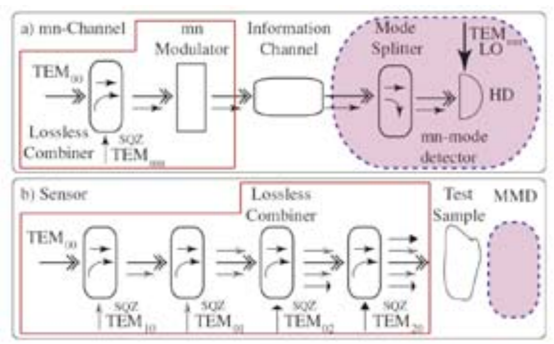

Figure 1: Schematic layout for a multi channel optical system. a) shows the components we have built and tested for a communication network. b) shows a spatial sensor.

During 2006 we have assembled an apparatus that contains two such high order modes of squeezed light and form a pair of spatially entangled beams. Our next goal is to demonstrate entanglement between the momentum and position of the two pairs of CW beams. We have already observed that the two beams are entangled as measured by the Duan criteria for separability. Our goal is to demonstrate EPR entanglement. The challenge is to overcome the many sources of loss and mode mismatch on our apparatus.

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Spatial mode discrimination in nonlinear parametric processes

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The nonlinears processes of second harmonics generation (SHG) and optical parametric amplification (OPA) play an important role in many optical experiments. They are primarily used to generate new wavelengths, such as frequency doubling of 1064 nm to produce pump beams at 532 nm and the inverse process of OPA to produce squeezed light.

While these technologies are well established and have been optimised for normal Gaussian beams we are facing the challenge to develop the best process for generating light in higher order modes. During the last two years we found ways of using the difference in propagation of the higher order modes to build systems that selectively convert light from one spatial mode at one frequency into a different spatial mode at another frequency.

We call this *spatial mode discrimination*. It is a technique that is using the difference of the Gouy phase shift in the various spatial modes and by carefully selecting the phase matching temperature of the nonlinear material we can determine the output mode shape. Fig. 1 shows a simple demonstration of this effect for the case of simple pass SHG in a Lithium Niobate crystal. We inject a TEM_{01} mode into the crystal and obtain a different output mode depending on the crystal temperature.

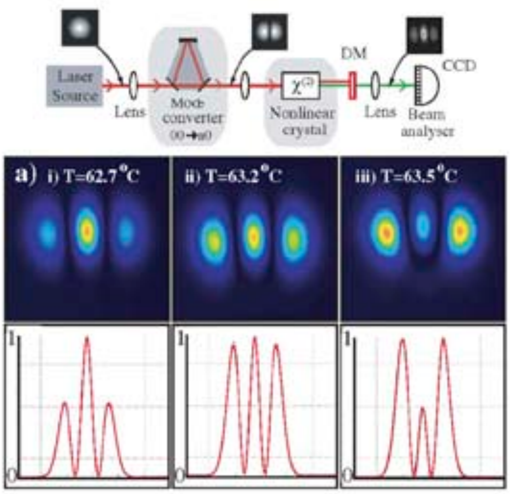

Figure 1: mode conversion for the case of simple pass SHG in a Lithium Niobate for three different crystal temperatures

During 2006 we have used this effect in our OPAs [1]. Inside an optical resonator spatial mode discriminator can be used to generate only a specific mode. In this way we were able to tune our squeezers to the TEM_{01} or TEM_{02} modes and produce spatially squeezed beams of high quality [2]. Our experiments have shown that the process of spatial mode conversion is very robust and reliable and can be achieved with very simple optical structures. We have applied for a provisional patent to protect the intellectual property and we are now setting up demonstration experiments that show applications such as the sensing of temperature or laser wavelengths with very high precision.

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Universal thermodynamics of strongly interacting Fermi gases

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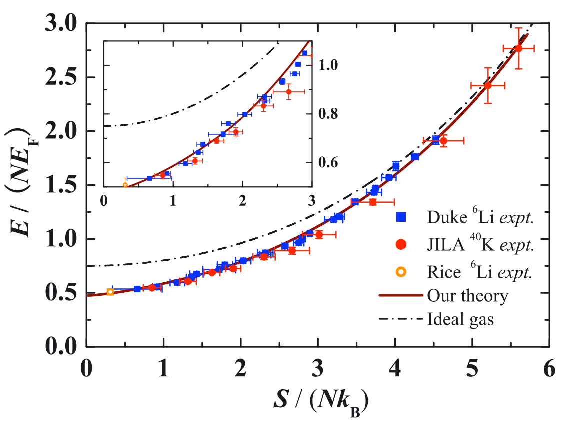
Strongly interacting Fermi gases are of great interest. Not only are fermions the most common particles in the universe, but they are also thought to have a universal behavior for strong interactions. Ultra-cold Fermi gases provide an exciting opportunity to test this prediction in the laboratory, thus allowing the interior properties of neutron stars to be investigated via experiments on earth. We demonstrate universality by comparing our strong interaction theory [1,2] with experiments on two different ultra-cold Fermi gases [3,4,5]. These measurements could be carried out with the SUT ^6Li apparatus.

In these experiments, the tunable magnetic field causes a Feshbach resonance or BCS-BEC crossover. This is a strongly interacting regime called the unitarity limit, which leaves the inter-atomic distance as the only relevant length scale. At this point, the gas should exhibit a universal thermodynamics, independent of any microscopic details of the underlying interactions [1,2]. *We find that, indeed, the thermodynamics is universal, and independent of which atomic species we compare with.*

Operationally, the energy is measurable simply from the radius of the strongly interacting fermion cloud, which shrinks due to the attractive interactions. The entropy of the gas is measured at various temperatures below 1 μ K by an adiabatic magnetic field sweep of the strongly interacting gas to a weakly interacting regime, where the entropy is known from the cloud size after the sweep. These ground-breaking experiments provide a precise measurement, accurate to the level of a few percent, with exceptional accuracy in the recent Duke experiments [3]. They offer an ideal opportunity to quantitatively test the universal predictions of microscopic many-body theories against experimental measurements.



Here we compare these experiments with our theoretical predictions on the entropy-energy relation of a strongly interacting trapped Fermi gas [6]. The agreement between theory and experiment is excellent for almost all the measured data, as shown in Fig. 1. This figure gives our predictions for the entropy (i.e., temperature) dependence of the energy of a harmonically trapped, strongly interacting Fermi gas. Exactly the same theory is used in all cases, with results from three different laboratories [3,4,5].

A key finding from the comparison is that the lowest experimentally accessible temperature of strongly interacting atomic gases at unitarity is in the range 0.10-0.15 T_F. This value, about half of the estimated critical temperature, has a significant impact on the determination of the universal many-body parameter β that describes the ground state energy of a Fermi gas in the unitarity limit. By removing the finite-temperature enhancement, we extract from the experimental data, $\beta \sim 0.59 \pm 0.07$, which agrees fairly well with the most accurate quantum Monte Carlo simulations, $\beta \sim 0.58 \pm 0.01$, and our theoretical predictions [1], $\beta = 0.599$. It is important to improve the accuracy of this measurement.

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Quantum atom optics using dissociation of a molecular BEC

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Producing and utilising quantum mechanical correlations between entangled particle pairs is a major theme in the ACQAO research program. Here, we report on our progress in the study of atom-atom correlations produced through dissociation of a BEC of molecular dimers. Owing to the analogy with the famous parametric down-conversion in photonics, molecular dissociation plays one of the central roles in quantum atom optics. In the case of molecules made of fermionic atoms, it also serves as an ideal playground for developing the new paradigm of *fermionic quantum atom optics*.

1. In view of the planned experiments with fermionic ^{6}Li at the SUT Node of ACQAO, we have commenced studies of dissociation of lithium molecular dimers into correlated fermionic atoms. As a first step we have studied the dynamics of dissociation and analysed the resulting atom correlations [1] using a simple analytically soluble model that relies on the undepleted molecular field approximation. Further details can be found in the ACQAO 2005 Annual Report.

2. We have also studied dissociation of a BEC of molecular dimers made of bosonic atoms, using first-principles positive-P simulations [2]. Further details can be found in the ACQAO 2005 Annual Report. Due to the exact nature of the method, we can investigate the correlations in both momentum space (which was the focus of Ref. [2]) and in position space. In 2006 we have finalised the analysis of the full spatial structure of the correlations in trapped inhomogeneous systems and simulated typical experimental procedures that involve time-of-flight expansion and absorption imaging [3].

3. In addition, we have implemented the pairing mean-field theory for the studies of molecular dissociation in one, two, and three spatial dimensions [4]. The pairing mean-field approach is intermediate between the exact first-principle methods and the crude undepleted molecular field approximation in that it takes into account the molecular depletion and atomic pair-correlations, but assumes that the molecular BEC remains in a coherent state at all times. While being an approximate theory, it is far less computationally demanding than exact first-principle methods, while still giving reasonably accurate predictions for dissociation durations corresponding to $\sim 50\%$ conversion.

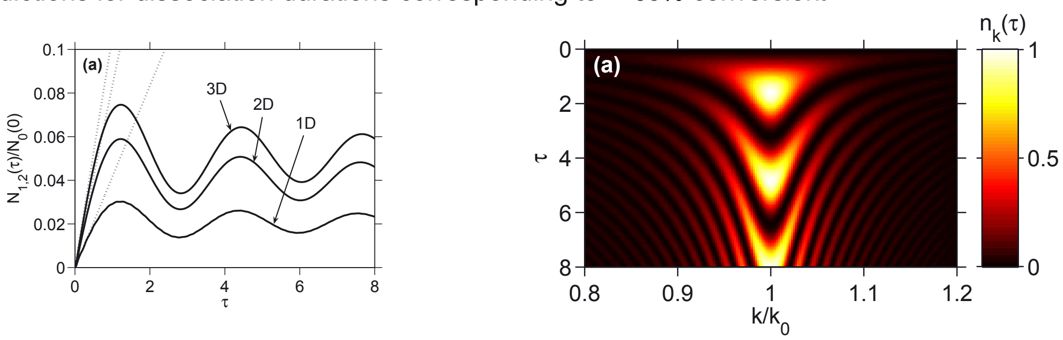

Figure 1: Left: Total number of fermionic atoms in each spin component $N_{1,2}(\tau)$ $[N_1(\tau) = N_2(\tau)]$ relative to the total initial number of molecules $N_0(0)$ as a function of a scaled time τ, in dissociation of molecular BEC in 1D, 2D and 3D, for a dimensionless detuning $\delta = -16$. Right: Radial dependence of the spherically symmetric 3D momentum distribution $n_{\mathbf{k}}(t)$ as a function of the scaled time and a scaled absolute momentum k/k_0, where $k = |\mathbf{k}|$.

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Optical Trapping of Ultracold Fermionic ^{6}Li Atoms

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In recent years most of the activity in cold atom research has involved bosonic atoms. However, there is a wealth of important physics to be found in cold fermionic systems. In particular, recent investigations by several groups [1] have demonstrated that it is possible to produce a highly stable molecular BEC composed of fermionic ^{6}Li$_2$ molecules, which exhibits lifetimes of some tens of seconds, compared to typically 100 μs in the case of quantum degenerate molecular gases that have been obtained from bosonic atoms. This very large enhancement of the lifetime is a manifestation of Pauli blocking and represents a major breakthrough in the field of quantum degenerate molecular gases. The objective of this project is to produce a molecular Bose Einstein condensate (MBEC) via the association of ultracold fermionic ^{6}Li atoms using a Feshbach resonance.

In our experiment a σ^- Zeeman slower is used to produce a continuous beam of ^{6}Li atoms at speeds low enough to load a magneto-optical trap (MOT). We currently have a flux of slowed atoms of 2x10^7 atoms/s loading the magneto-optical trap (MOT) with approximately 10^8 atoms. The MOT is formed inside a custom-made glass cell, with a background pressure of 10^{-11} Torr, and has a measured lifetime of approximately 60 s. We transfer the atoms from the MOT to a far-off-resonant optical dipole trap (FORT) in which the atoms are evaporatively cooled and can form molecules. The FORT consists of a focussed beam from a 25 W single-frequency Yb:YAG laser at 1030 nm. We control the scattering length of the atoms via a Feshbach resonance at 834 Gauss. Initial evaporation in the FORT has reduced the temperature of the atoms to less than 3μK, which is close to the estimated Fermi temperature. This is performed at magnetic field strengths that enhance three-body recombination to form ^{6}Li$_2$ dimers. The next experimental step is to continue evaporation and further condense to form a MBEC of ^{6}Li$_2$ molecules.

In collaboration with the ACQAO theory group at the University of Queensland, we propose to use the MBEC to study the dissociation of the quantum degenerate molecules into correlated (entangled) atom pairs [2], and to investigate the coherent interaction between the MBEC and a quantum degenerate atomic gas.

Theoretical research on molecular BECs generated from cold atomic gases is also being carried out. Distribution Functional Methods for treating problems in quantum-atom optics are being developed. In many situations, such as multimode lasers (bosons) and degenerate Fermi gases (fermions), a large number of modes (single atom states, electromagnetic field modes) are required. Rather than treating these modes explicitly, approaches have been developed in bosonic systems, where the density operator can be used to define Quasi-Distribution Functionals. The next step will be to extend this approach to fermionic systems. The approach would then be applied to processes such as the dissociation of bosonic molecular BECs into pairs of fermionic atoms, in which both types of quantum statistics are involved.

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Self-trapped matter waves and vortices in optical lattices

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Weakly interacting Bose-Einstein condensates (BECs) in optical lattices possess a band-gap structure in their Bloch-wave spectrum, which modifies the dispersion properties of BEC wavepackets and enables nonlinear localisation of a repulsive condensate in the spectral gaps in the form of bright atomic solitons. The experimental observation of gap solitons near the edge of the first spectral band in a shallow 1D optical lattice required preparation of a weakly nonlinear BEC with a small number of atoms [1]. More recently, a seemingly different localised state with steep edges and a *large number of atoms* was observed [2], where the increasing nonlinearity of the BEC wave packet enabled the transition from the diffusive regime of condensate expansion in a deep one-dimensional optical lattice to the regime where the initial expansion stopped and the width remained finite. This effect has been attributed to the *self-trapping* mechanism of energy localisation described by discrete tight-binding nonlinear models.

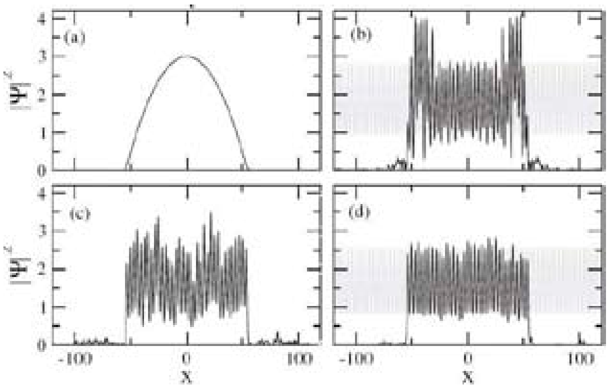

Figure 1: Non-adiabatic excitation of a gap wave in a 1D optical lattice. An initial state (a) prepared in an anisotropic quasi-1D trap is suddenly released into an optical lattice. The initial expansion in the lattice (b) stops and a self-trapped state forms (b,d). Nonlinear ground (Bloch) state is shown in (b) and (d) for comparison.

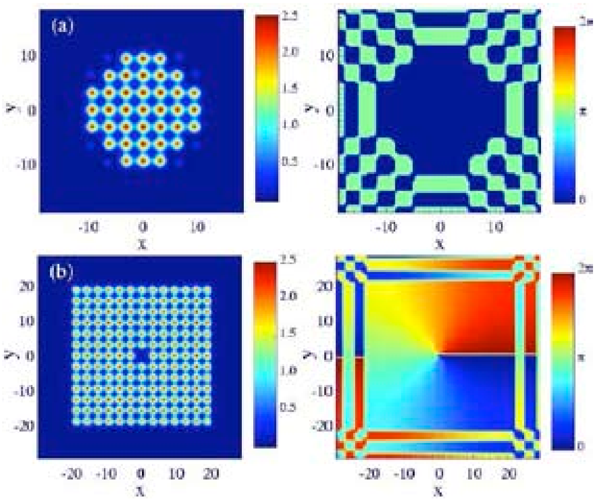

Figure 2: Self-trapped states in a 2D lattice shown with the phase distribution: (a) a non-square state in a "square" optical lattice, and (b) a broad spatially localised gap vortex.

We have discovered that the observations of Ref. [2] can be explained by the excitation of a new type of gap state which serves as a missing link between the two fundamental types of nonlinear states in the lattice, the spatially extended nonlinear Bloch waves, and the spatially localised gap solitons. These new states, "gap waves", may be viewed as truncated nonlinear Bloch waves localised in the gaps of the linear Bloch-wave spectrum [see Fig. 1(d) and 2(a)]. Although the gap waves can be excited only above a certain density threshold, they exist well beyond the tight-binding regime.

We have also demonstrated that these novel gap states can be generated experimentally in any dimension, and for arbitrarily large initial atom numbers, by *nonadiabatic* loading of the BEC into a stationary optical lattice [see Figs. 1]. Moreover, a gap wave can be used as a background that supports nontrivial phase states formed by phase imprinting, and hence can provide a means for generating dynamically stable stationary gap vortices [4] in an optical lattice [see Fig. 2(b)].

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Localisation vs heating of Bose-Einstein condensates in optical lattices

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A striking manifestation of the interplay between the periodicity of the optical lattice and nonlinearity of the matter wave is formation of bright atomic solitos in a Bose-Einstein condensate (BEC) with *repulsive* nonlinear interactions [1]. This nonlinear localisation occurs within the *gaps* of the band-gap spectrum of the matter Bloch waves due to the anomalous diffraction of matter waves at the edge of the Brillouin zone (BZ). The observation of a single gap soliton [1] required preparation of a *small* condensate at the BZ edge in a one-dimensional (1D) lattice moving with a constant velocity. In contrast, a large BEC prepared at the BZ edge exhibits dynamical (modulational) instability [2], which causes significant loss of condensed atoms to the thermal fraction. By modeling the mean-field dynamics of the BEC beyond the onset of dynamical instability, we have demonstrated that the modulational instability can lead to the localisation of a BEC in the form of *gap soliton trains* [3]. However, it remained unclear whether the formation of a soliton train at the BZ edge could still occur in the presence of the enhanced heating.

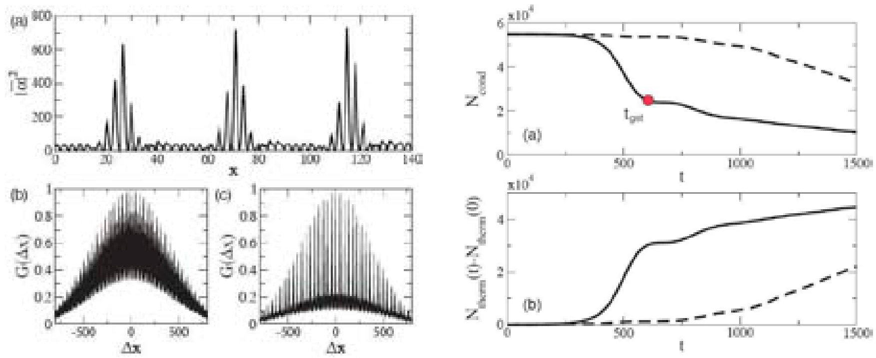

Figure 1: Left: Localisation signatures with initial phase imprinting. Shown are (a) BEC density after 366 ms at the BZ edge and averaged density correlation function (b) before and (c) after the soliton train formation. Right: Loss of BEC atoms (top) and growth of the thermal fraction (bottom) during 2.4 s of the BEC evolution at the BZ edge with (dashed) and without (solid) phase imprinting. The red dot marks the time of the soliton train formation.

By performing stochastic Wigner simulations of the atomic field, we analysed quantum effects in the dynamics of a BEC at the edge of the Brillouin zone of a 1D optical lattice [4]. We found that quantum fluctuations trigger the dynamical instability of the Bloch states of the BEC which leads to the generation of arrays of *gap solitons*. The formation of the soliton trains can be accelerated by an initial periodic phase imprinting [Fig. 1(a)]. Our simulations of the instability-induced growth of the thermal fraction [Fig. 1(right panels)] confirmed that there are regimes in which the anomalous heating *does not suppress the formation of the soliton train*. The solitons are clearly seen in the simulations equivalent to a “single shot” experiment. However, without the initial phase imprinting, they are no longer detectable after averaging over many realisations. Instead the spatial density correlation function can provide a clear, experimentally detectable signature of the nonlinear localisation both with [Fig. 1(b,c)] and without phase imprinting [4].

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Quantum dynamics of a coupled atomic-molecular gas in an optical lattice

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Ultracold quantum gases of bosonic and fermionic atoms in optical lattices are highly versatile systems for fundamental studies of quantum many-body physics. They are robust to experimental manipulation and can be described by well-defined theoretical models. Such experiments offer the possibility of forming novel states of ultracold matter, and have the potential for new insights into quantum many-body phenomena. Recent experiments have extended the studies of quantum gases in optical lattices to molecules, using either Raman photoassociation or Feshbach resonance techniques [1].

Motivated by these new experiments and their possible future extensions at the SUT Node of ACQAO, we have commenced a theoretical study of the quantum dynamics of a coupled atomic-molecular system in a Mott state of an optical lattice [2]. As a first step we consider simple cases corresponding to small numbers of atoms and molecules at a single lattice site, without tunnelling, and study the association and dissociation dynamics of the coupled atomic-molecular gas. We treat both the cases of molecular dimers made of bosonic and fermionic atoms, and find a rich variety of periodic and aperiodic solutions (some analytic) that correspond to Rabi-like oscillations between the atomic and molecular states. The solutions can be used as a diagnostic tool for probing the underlying inter-particle interactions, for determination of the distribution of lattice site occupancies, and for precision spectroscopy of the new ro-vibrational structure of the molecules formed under lattice confinement.

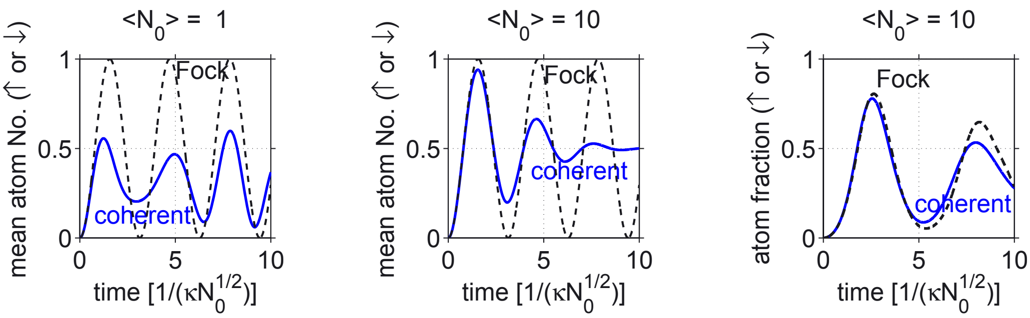

Figure 1: Average number of each type (spin up or down) of fermionic atoms in the lattice mode as a function of a scaled time, dissociated from an average of one (left graph) and ten (middle graph) molecules per lattice site. The two lines are for initial coherent or Fock molecular states. The graph on the right shows the fraction of atoms, relative to the total initial number of molecules, in the case of dissociation into bosonic atoms.

When the quantum gases are in the Mott insulator regime we may treat each lattice site independently, so that the whole of the lattice dynamics can be obtained from analysis of one site. Each site is treated as a Bernoulli trial with a time dependent probability of the occupation numbers. When the insulator is melted and the atoms cross into the superfluid regime, the theoretical treatment is more complicated and we are developing methods to investigate this transition. So far we have investigated up to three interacting sites and are quantifying the effects of the hopping parameters, collisional interactions and molecular association strengths on the crossover regime.

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Many-body quantum physics of ultracold atoms in few-site systems

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The many-body quantum nature of ultracold atoms becomes important in the systems of low dimensionality, the systems with strict symmetry constraints, degeneracy, or strong interaction. Examples include low-dimensional gases, condensates with strong atom-atom interaction, and ultracold atoms confined in double-well potentials or optical lattices. To explore many-body quantum effects in the systems with degeneracy, we employ the second-quantisation theory for coupled multiple modes which obey Hubbard-like Hamiltonians. Using this formalism, we explore the subtle many-body quantum effects in the systems of ultracold atoms confined to two or three lattice sites.

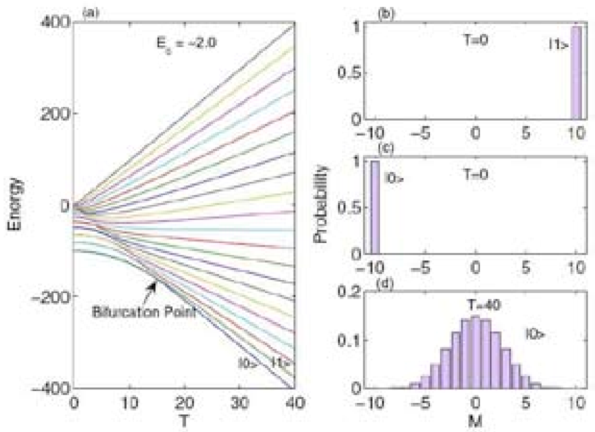

Figure 1: (a) The energy spectrum, the (b) ground, and (c) first excited states for $N = 20$ bosons in a Bose-Josephson junction with negative charging energy and zero mode coupling ($M = -N/2, -N/2+1, ..., N/2$). (d) The ground state for large mode coupling (tunneling).

For a two-site system (a Bose-Josephson junction), we have demonstrated that the combination of nonlinear and many-body quantum effects can be used to realise a Heisenberg-limited Mach-Zehnder interferometry. The scheme is based on N bosons confined in a double-well potential in a tight-binding regime. The degeneracy of the ground and the first excited state is controlled by the dynamically tunable tunneling rate. By using the ground and the first excited state as two paths of an interferometer and achieving the beam splitting and recombination via adiabatic passage through dynamical bifurcation (Fig. 1), it is possible to realise a Mach-Zehnder interferometry. By fixing the charging energy to negative values, the existence of a path-entangled state is ensured, which enhances the phase masurement precision to the Heisenberg limit [1].

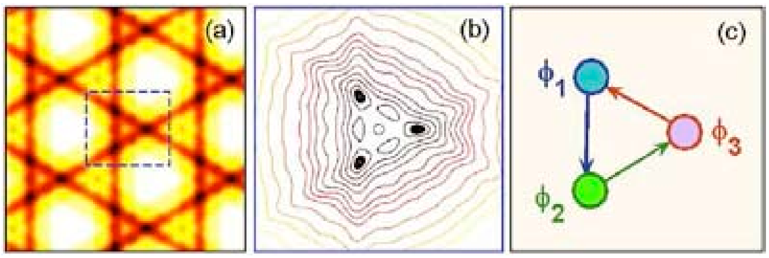

Figure 2: (a) Bosons in a strongly trimerized Kagomé lattice can be reduced to three-site Bose-Hubbard rings. (b) A three-site system (c) generated by combining a two dimensional harmonic potential with the Kagomé lattice.

Using a three-site Bose-Hubbard model (Fig. 2), we have analysed how the classical discrete vortices "melt" under the action of quantum fluctuations [2]. In particular, we studied the phase coherence and the spatial correlations in the stationary states with nontrivial phase and revealed that the breakdown of these coherent structures through quantum fluctuations accompanies the superfluid-insulator crossover in the system of ultracold atoms confined to three lattice sites [2].

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Nonlinear localisation of spinor condensates in optical lattices

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The development of optical trapping techniques for Bose-Einstein condensates (BECs) has enabled the confinement of atoms independently of their spin orientation in so-called *spinor condensates*. Diverse experimental and theoretical activities had aimed to characterise the effect of the spin degree of freedom on the macroscopic quantum state, and a multitude of exciting phenomena which are not present in a single component BEC have been revealed. One of the most frequently used optical traps for ultra-cold matter is an optical lattice. However, up to now, the effect of the spin degree of freedom on the key properties of BECs in periodic potentials has not been fully explored.

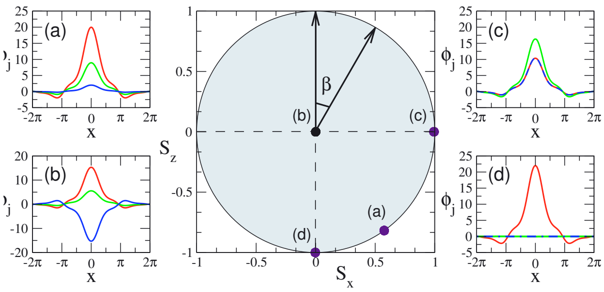

Figure 1: Examples of spatial structure of the (a,c,d) ferromagnetic-type (in-phase) and (b) polar-type (out-of-phase) gap solitons in a polar (^{23}Na) condensate in an optical lattice of moderate depth. Red, green, and blue lines show the ϕ_{-1}, ϕ_0, and ϕ_{+1} hyperfine components, respectively. The corresponding values of the local spin vector $\vec{S} = (\mathcal{S}_x, \mathcal{S}_y, \mathcal{S}_z)$ are plotted in the cross-sectional plane $\mathcal{S}_y = 0$ of the 3D spin sphere (shaded); β is the Euler rotation angle.

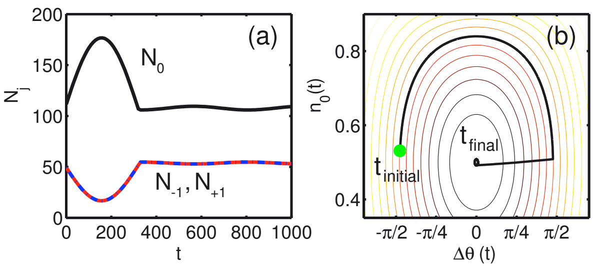

Figure 2: Non-equilibrium dynamics of localised states in a ferromagnetic $^{87}\mathrm{Rb}$ BEC. (a) Oscillations of the populations in $m_F = -1$ (red), $m_F = +1$ (blue, dashed-dotted) and $m_F = 0$ (black) hyperfine components, arrested due to the quadratic Zeeman effect, by application of a 1.4 ms magnetic field pulse of magnitude $B = 1$ Gauss. (b) Trajectories in the phase space (population in the $m_F = 0$ component vs relative phase between $m_F = \pm 1$ components) corresponding to (a).

By employing the system of three coupled Gross-Pitaevskii equations for the condensate wavefunctions in different hyperfine states, we modeled the nonlinear behaviour of spin-1 BECs with repulsive spin-independent interactions and either *ferromagnetic* or *anti-ferromagnetic* (polar) spin-dependent interactions, loaded into a one-dimensional optical lattice potential [1]. We demonstrated that both types of BECs exhibit dynamical instabilities and may form spatially localised multi-component structures. The localised states of the spinor matter waves take the form of *vector gap solitons* (Fig. 1) and *self-trapped waves* [2] that exist only within gaps of the linear Bloch-wave band-gap spectrum. Of special interest are the nonlinear localised states that do not exhibit a common spatial density profile shared by all condensate components [1], and consequently cannot be described by the *single mode approximation* (SMA) frequently employed within the framework of the mean-field treatment. We show that the non-SMA states can exhibits Josephson-like internal oscillations and *self-magnetisation*, i.e. intrinsic precession of the local spin. Finally, we demonstrated that non-stationary states of a spinor BEC in a lattice exhibit coherent undamped spin-mixing dynamics, and that their controlled conversion into a stationary state can be achieved by the application of an external magnetic field (Fig. 2). This opens up possibilities for controlled manipulation of a spinor condensate as a means of quantum state engineering, which is an essential element of quantum computing schemes.

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Spin-polarized superfluid Fermi gases

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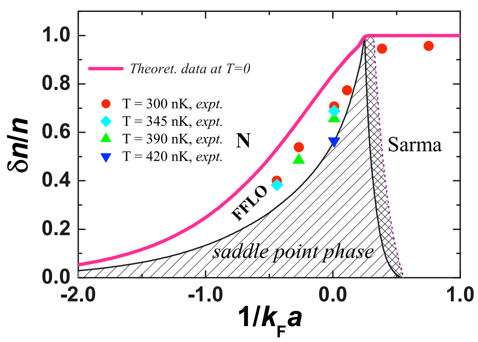
Recently, three experiments, reported in Science and Nature[1, 2, 3], have studied the properties of spin-polarized ultra-cold Fermi gases. This very new area has attracted a great amount of interest in widely varying fields ranging from condensed matter, atomic, molecular and optical physics, to particle and astro physics. An experimental program in ultra-cold fermionic ^6Li near a Feshbach resonance is underway at the SUT node of ACQAO. The work described here provides theoretical support for possible experimental investigations of new forms of superfluidity near the Feshbach resonance.

Since the usual BCS pairing requires an equal number of atoms in each spin state, the presence of spin population imbalance leads to some exotic forms of pairing, such as 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 spin-polarized fermionic superfluidity remains elusive and has been the subject of debate for decades. Motivated by these significant experimental developments, we have studied the phase diagram and thermodynamics of the ground state and vortices in spin-polarized Fermi gases.



Firstly, by using a mean-field approach we propose a phase diagram at zero temperature for a spin-polarized Fermi gas at the BCS-BEC crossover. We construct the phase boundary of superfluid-to normal transitions and compare it with measurements by Zwierlein et al. The agreement is qualitatively good. We also include quantum fluctuations using NSR theory. We determine the transition temperature at fixed chemical potential imbalance, and give the finite-temperature phase diagram[4, 5].

We also consider trap effects by using both the Bogoliubov-de Gennes equations and the local density approximation at finite temperature. We find that a bimodal structure emerges in the density profile of the minority spin state at finite temperature, as observed in experiments. The superfluid transition temperature as a function of the population imbalance is determined, and is shown to be consistent with recent experimental measurements[6].

Next, we have analyzed the effects of creating superfluid vortices, and show that this results in a core of trapped normal fermions, which can be visualized experimentally using phase-contrast imaging[7]. Finally, we have treated the exactly soluble one-dimensional case, obtained the complete phase-diagram which demonstrates the existence of an exotic FFLO phase, and shown for the trapped case that there is an experimentally accessible signature via a collective mode frequency measurement[8].

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Phase-space simulation methods for quantum dynamics

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The development of tractable methods to simulate the dynamics of strongly correlated quantum systems of bosons and fermions is the goal of this research stream in quantum phase-space methods. The methods are based on the non-classical, positive-P techniques that were originally developed in quantum optics and are now being tailored to systems of massive particles, i.e., electrons, atoms or molecules. The previous methods can be extended and improved through stochastic gauges or novel basis sets.

The gauge techniques are able to deal with extremely complex irreversible master equations as well as unitary dynamics. The application of stochastic gauge representations to the general case of interacting bosonic systems has been analysed in depth in recent papers[1]. Using stochastic gauges that give real weights, we have been able to apply Monte Carlo techniques such as the Metropolis algorithm to real-time quantum dynamics[2].

Simulation methods based on a generalised Gaussian representation are a powerful alternative to coherent-state methods. These novel techniques are being tested on dynamical simulations of atoms and molecules in optical lattices. Examples include simple models of the molecular association and dissociation of fermionic and bosonic atoms, as well as tunnelling dynamics in double-well potentials[3].

The truncated Wigner method has been found to give predictions very close to those of an exact matrix method for tunnelling in a double well potential where reasonable numbers of atoms are involved. However, it was found that for photoassociation in an optical lattice, the truncated Wigner can be inaccurate for low occupation numbers. This work is being extended to find more accurate methods[4].

We are also developing a hybrid simulation method that combines the best features of the positive-P and truncated Wigner methods. The intended applications are to atomic Bose-Einstein condensate systems, atom lasers produced from those BECs and various outcoupling and detection scenarios. In systems with a small number of highly occupied modes—the condensed modes—and a large number of modes with small occupation numbers, the Wigner representation should work well for the condensed modes while the positive-P representation should be successful with the other modes. The formalism has been developed and has been applied to simple reservoir models to test the behaviour of the sampling error in a multimode system[5].

In collaboration with L. I. Plimak and W. Schleich (Ulm) and M. Fleischhauer (Kaiserslautern), we have developed a method to calculate time-normally ordered correlation functions in the Wigner representation. This uses Kubo's linear response relation to calculate the expectation values of two-time commutators[6].

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Phase-space representations for solving quantum many-body problems

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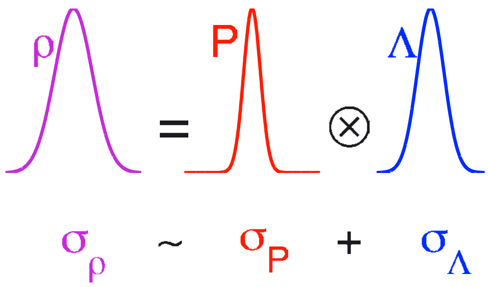
The physics of quantum many-body systems underlies the whole ACQAO research program, and the methods outlined here are central to the analysis of quantum correlations in ACQAO experiments. The goal of this research stream is to develop numerical techniques to solve quantum many-body problems at any given temperature. The methods are based on adapting and extending phase-space representations originally developed for quantum optical systems, to take into account the stronger interactions that occur in ultracold atoms.

The most fundamental way to generalise the previous phase-space methods is through the use of new operator bases, which determine the basic structure of the method and its suitability to different physical situations. We have developed the formalism for a generalised Gaussian basis for fermions. Besides generalising both the BCS ground states and noninteracting thermal states, which are both of physical relevance in ultracold Fermi gases, the Gaussian basis[1] provides a complete and positive representation of *any* physical fermionic state. Using these results, we have developed a class of quantum simulation techniques for Fermi systems[2].

$$\hat{\rho} = \int P(\vec{\lambda})\hat{\Lambda}(\vec{\lambda})d\vec{\lambda}$$



Left: Phase-space representations arise from an expansion P of the density matrix $\hat{\rho}$ over an overcomplete operator basis $\hat{\Lambda}$. **Right**: A good choice of basis can lead to a more efficient representation.

To obtain more precise calculations at low temperatures, the Gaussian techniques require the use of stochastic gauges. We have investigated the properties of the underlying nonlinear multiplicative SDEs, which are of higher-order than is usually encountered in other phase-space techniques. Based on this, we have developed and are now testing strategies that either minimize the tails that tend to develop at low temperatures, or, if the weights are allowed to be complex, to remove them totally[3, 4].

A more recent research program has been to apply these generalised phase-space methods to exact calculations of ultracold *bosons* in lattices. The topics of interest are quantum correlations in finite, trapped 1D gases (a UQ-Swinburne collaboration), and scalar and spinor BECs in rotating 2D lattices. In the bosonic case, the general Gaussian basis incorporates both coherent-state and thermal subsets, each of which provides a complete basis. There is thus a choice of strategies, from gauge-P augmented with number variables for onsite the on-site interactions, to the full Gaussian basis. To complement the phase-space study of the 2D lattice system, we are also applying and benchmarking phenomological approaches that treat vortices in such systems as a gas of interacting particles.

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Theory of non-Markovian decay of a cascade atom in high-Q cavities and photonic band-gap materials

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The study of open quantum systems, in which the interaction of the quantum system with the environment is taken into account, is of fundamental importance in several areas of physics, including quantum optics, quantum measurement theory and degenerate quantum gases. In many cases the interaction between the quantum system and the environment (also referred to as the reservoir) involves coupling constants and reservoir mode densities that have slowly varying frequency dependences. In such cases the dynamical behaviour of the quantum system allowing for its interaction with the environment can be described by Markovian master equations. However, in recent years there has been an interest in open quantum systems where the conditions required for Markovian behaviour do not necessarily apply. Cases include atom lasers, quantum Brownian motion, systems with conditioned evolution (such as associated with photodetection), decoherence in large scale quantum computers and in macroscopic systems generally. A further non-Markovian situation occurs for atomic systems coupled to structured reservoirs of electromagnetic (EM) field modes, where either the coupling constants or the mode density (or both) change rapidly with frequency. This situation can occur for atoms in high-Q cavities or in photonic band-gap (PBG) systems.

The dynamics of a three-level atom in a cascade configuration, with both transitions coupled to a single structured reservoir of quantized field modes and including two-photon excitation of the reservoir from both emitting sequences, is treated via the essential states approach, using Laplace transform methods applied to the coupled amplitude equations [1]. Non-resonant transitions are included in the model. Two different cases of structured field modes are considered, namely a high-Q cavity and a photonic band-gap system, in which the respective reservoir structure functions involve Lorentzians. In all cases non-Markovian behaviour for the atomic system can be found, such as oscillatory decay for the high-Q cavity case and population trapping for the photonic band-gap case. A Markovian master equation approach is also applied [1], in which the atomic system is augmented by a small number of discrete quasimodes (or pseudomodes), which in the quasimode approach themselves undergo Markovian relaxation into a flat reservoir of continuum quasimodes. Results from this method are found to be identical to those from the essential states method. This shows that complicated non-Markovian decays of an atomic system into structured EM field reservoirs can be described by Markovian models for the atomic system coupled to a small number of pseudomodes or quasimodes. A similar approach of turning a non-Markovian problem into a Markovian one may be applicable in other systems.

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** High impact article

PERSONNEL AND ASSETS

People are the most important part of our Centre. We started with an excellent group of people and have given them improved opportunities for research through reduced teaching loads, new and upgraded laboratories and offices, as well as the opportunity to collaborate freely within ACQAO and throughout the world. The longer term funding has helped to focus the team on ambitious research projects, and the synergies provided by interactions within the Centre have created new research opportunities.

Our very effective administrative team of Ruth Wilson COO, Max Colla at ANU, Tatiana Tcherchova at SUT, Linda Schumacher & Stephanie Golding at UQ, Deborah Bordeau & Wendy Quinn (ANU IAS) takes the responsibility for the financial and organisational work, creating more time for our researchers.

We have been able to attract and retain our excellent staff. In 2006 Elena Ostrovskaya and Chaohong Lee obtained their own ARC fellowships within ACQAO.

We are particularly proud that we have attracted talented Australians who have worked overseas back to Australia. In 2006 we have Michael Volk and Cristian Figl from Hannover working in ACQAO. Several excellent students have chosen ACQAO for their PhD program (Oliver Topic from Hannover, Jiri Janousec from DTU Copenhagen, Daniel Oblak from NBI Copenhagen and Rudolf Gati from Heidelberg) and we are actively seeking to increase our graduate student program. A full list of the complete ACQAO staff is given on page 54.

ACQAO quantum optics laboratory at ANU Faculties

The other big asset is our research laboratories. We have fully functioning, custom made laboratories at both ANU and SUT. We continue to invest in our laboratory equipment. During 2006 we had extra support through an ANU major equipment grant for new laset technology for the He* BEC project at the ANU. Our total equipment purchases make up about 30% of our entire budget and these investments make our groups competitive on a global stage.

ACQAO team 2006

Collaboration and Linkage

The scientific links within our Centre have grown and are now an important part of our activities. In addition we have strengthened our scientific links with the international research community, particularly in Europe. We have intensified the scientific exchange with our official partners in Hannover, Erlangen, Amsterdam, Paris, London, Dunedin and Auckland. They all received visits from ACQAO staff and some hosted visits of students.

Particularly intensive exchange relationships exist with the following international partners:

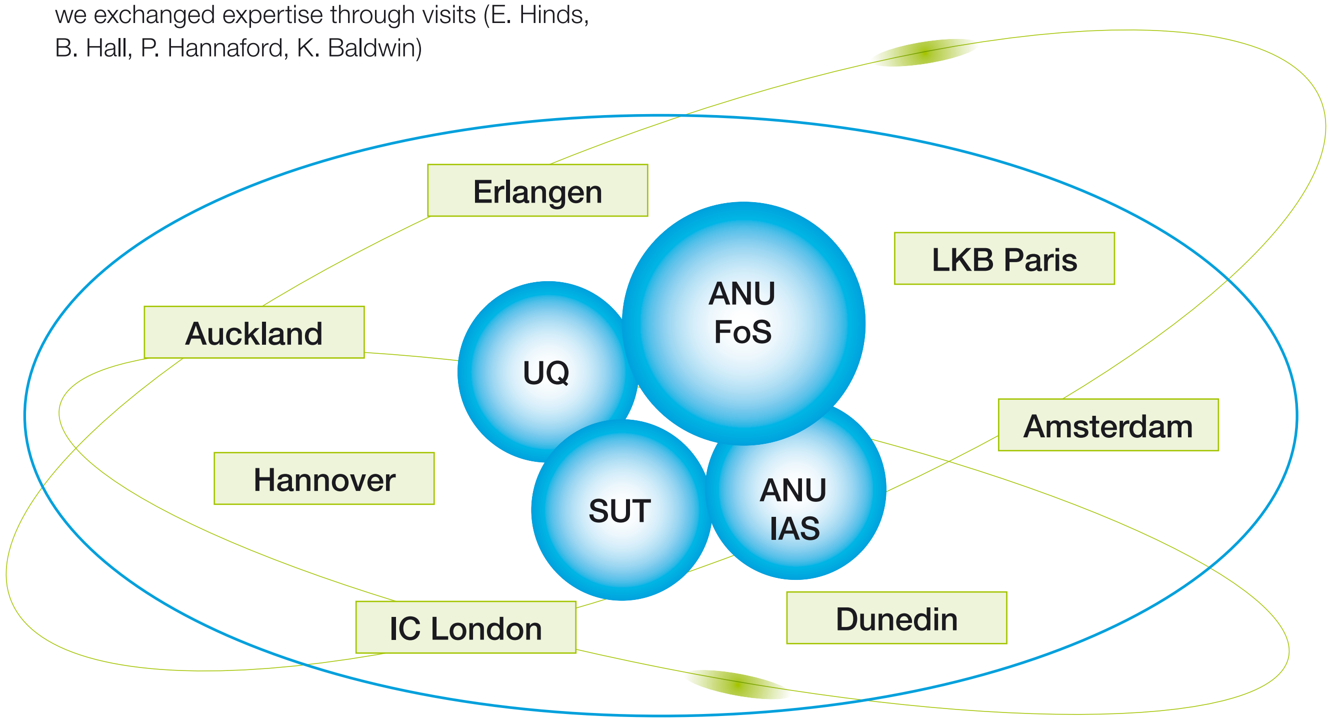
- IFRAF and LKB in Paris on quantum imaging and atom laser development and fundamentals of atom optics with two cotutelle projects (V. Delaubert and J. Dugue) have been established, and staff have an extensive exchange of staff (Hans-A. Bachor, K. Kheruntsyan, P. Drummond, M. Leduc)
- SFB 407 in Hannover on BEC-on-a-chip and optical entanglement staff have visited (M. Volk, Hans-A. Bachor, W. Ertmer, E. Tiemann)
- Imperial Collge London on BEC-on-a-chip where we exchanged expertise through visits (E. Hinds, B. Hall, P. Hannaford, K. Baldwin)
- Max Planck Institut Erlangen on optical entanglement where we exchange staff (O. Glöckl, Hans-A. Bachor, J. Corney, P. Drummond, U. Andersen)
- Amsterdam and Paris where we exchanged expertise between the three He* BEC experiments (K. Baldwin, W. Vassen, M. Leduc, A. Aspect)
- Dunedin and Auckland where we have started a joint project (M. Davis, B. Blakie) and continued with our exchange visits (W. Bowen, P. Drummond, H. Carmichael).

Additional intensive collaborations include:

NIST Gaithersburg to compare theory and experiments in low dimension BEC (P. Drummond, W. Phillips, K. Baldwin)

NIST Boulder on high precision spectroscopy and the Fermion statistics (Dr Ken Baldwin, D. Jin, J. Hall)

Universität Innsbruck with exchange visitors in the area of BEC techniques and precision measurement (K. Baldwin, R. Blatt)



A multitude of links and exchanges between the Centre and the international partners

DTU Copenhagen with the development of SHG based sensors and generation of spatial squeezed light (P. Buchhave, M. Lasen, H-A. Bachor)

Van der Waals Zeeman Institute, Amsterdam on the development of BEC simulation techniques (P. Drummond, P. Deuar)

ETH Zurich on fermion simulation techniques (J. Corney, X. Liu)

Kirchhoff Institut fur Physik, Universitat Heidelberg on nonlinear dynamics of BEC in optical lattices (E. Ostrovskaya, Y. Kivshar).

All these exchanges bring expertise to Australia, enhance our international profile and in several cases have led to joint publications listed on page 41. At the moment we are investigating the options for ACQAO participation in European research networks.

We have signed a contract with the Sonderforschungsbereich SFB 407 in Hannover and the CNRS/IFRAF France to organise annual quantum-atom workshops over three years — one in each country — and in February 2006 we hosted the Quantum-Atom Optics workshop at the ANU campus at Kioloa. In December we contributed to the Australian Institute of Physics Congress in Brisbane and held our own meetings at the same location. These scientific meetings provide unique opportunities for our students and staff to meet their peers, to discuss science and gain new laboratory experiences.

Professor Aspect (France) lecturing at Kioloa workshop

Within Australia we have maintained and built up many working contacts with research groups outside the Centres of Excellence with the aim to support as much research in quantum and atom optics as possible.

With this in mind, ACQAO was instrumental in bringing together the three Centres of Excellence in optical and quantum science and technology — ACQAO, the Centre for Ultrahigh bandwidth Devices for Optical Systems and the Centre for Quantum Computer Technology — to present and discuss research topics of mutual interest and future collaboration. The workshop was chaired by Dr Ken Baldwin and was held in Sydney where 80 scientists from the three Centres participated, including the international scientific advisory Board of ACQAO and the renowned philosopher with interests in quantum physics — Professor Huw Price.

ACQAO and International participants at Kioloa workshop, February 2006

Ruth Wilson and Dr Ken Baldwin (ANU), and Prof Michele Leduc (France) at Kioloa

Commercialization

While our research projects focus entirely on strategic fundamental goals, which will be published in the open literature, we are using every opportunity to create additional intellectual property. Such IP will be shared between the inventors and the host universities as defined in our IP agreement.

In 2006 our investigations on spatial mode conversion with the SHG, led by C. Harb and including D. Pulford from DSTO, have resulted in a provisional patent and we are now investigating applications in photonics and metrology. In addition, the UQ group is further developing the software code: e**X**tensible **m**ulti **d**imensional **S**imulator (XmdS) which is available on http://www.xmds.org.

Awards received

Throughout 2005 the following members of the Centre were rewarded with distinctions that indicate the high profile of our staff:

Professor Ping Koy Lam and his quantum optics team were awarded a Eureka Medal for their innovation in optical communication and in particular cryptography.

Professor Yuri Kivshar was appointed as a Fellow of the American Institute of Physics.

Dr Ken Baldwin was awarded Fellowship of the Institute of Physics (UK).

Dr John Close was recognised by the Carrick Institute with a prestigious award for his contributions to the integration of undergraduate students into the research environment within ACQAO.

Roger Senior received a University medal from the ANU for his Honours project in ACQAO.

KEY PERFORMANCE INDICATORS (KPI)

The performance of the Centre can be judged by both the quality and the quantity of our research results and the impact we have on the research community and the wider public.

All our projects are now in full operation and we are producing an impressive set of results. The theory core continues to set the pace and publishes both new ideas that are being adopted in other laboratories as well as detailed proposals for future experiments within our Centre.

Five of the experimental projects have produced excellent new results which are presented in high impact journals such as Physical Review Letters (PRL).

All of these outcomes are described in the Science section (pages 11–40) of this report.

For 2006 we have exceeded the projected KPIs with 49 publications. Amongst these are 11 publications with particularly high impact factor in *Phys. Rev. Letters*. We also achieved a high rate of citations with an average of 8.2 citations for all our 2003/04 publications.

We succeeded in recruiting more new postgraduate students (8) and have a steady rate of postgraduate completions (3 in 2006). The number of Honours students (10) is well above our target.

We have exceeded our goals in regard to the number of visitors who came to Australia (35) to see our work and the number of invitations (20) we received to address international conferences. We have formed an international student network with our partners in Paris and Hannover and this year an international meeting in Australia. Four overseas students and two cotutelle students worked in our laboratories.

At the same time, we have maintained a widespread teaching program at all three Universities, with a total of 17 undergraduate and 9 professional courses in 2006.

We have presented our ideas and goals to a wide section of the Australian community with 10 different outreach activities.

Key Performance Indicators (KPI)

Key Result Area	Performance Measure	Target	Outcome
Research Findings	Quality of publications International Ref. Journals with an impact factor >5	3	11
	Number of publications/year	20	49
	Number of patents/year	0.3	1
	Number of invitations to address and participate in international Conferences/year	4	20
	Commentaries in professional journals National and international/year	3	1
Research Training and Professional Education	Number of postgraduates recruited/year	5	8
	Number of postgraduates completions/year	4	3
	Number of Honours students/year	5	10
	Number of professional courses to train non Centre personnel/year	2	9
	Number and level of undergraduate and high school courses in the Priority area/year	7	17
International, National and Regional Links and Network	Number of International visitors/year	10	35
	Number of national and international workshops/year	1 international 1 national	1 2
	Number of visits to overseas Laboratories	18	63
	Contact with researchers related to the philosophical aspects of Quantum Physics	1	2
End-user Links	Number and nature of commercialisation activities	2	0
	Number of government, industry and business briefings/year	2	4
	Number of Centre associates trained In technology transfer and commercialisation	2	1
	Number and nature of Public Awareness programs	4	10

OUTREACH/MEDIA

Our Centre has steadily established recognition with the media over the past few years while ACQAO personnel were involved with Outreach activities throughout 2006.

Dr Wayne Rowlands from the ACQAO Swinburne Node in Melbourne was invited to present the 2006 Youth Lectures by the Queensland Branch of the Australian Institute of Physics (AIP). His action-packed talks based on cold-atom physics, with emphasis on the work being done in Swinburne as part of the ARC Centre of Excellence for Quantum-Atom Optics was enthusiastically received by students in remote and regional areas of Queensland. Dr Rowlands visited Mt Isa, Townsville, Rockhampton, Gold Coast, Toowoomba as well as Brisbane.

Media coverage of the lectures included an article in the Mt Isa North West Star newspaper and a TV News story on the WIN network in Rockhampton.

Dr Wayne Rowlands in his Swinburne laboratory

We have continued our strong involvement with the national student programs such as the National Science Youth Forum, the RioTinto Science Olympiads and Questacon in Canberra. ACQAO staff at ANU contributed to all these programs and reached more than 400 students and 35 teachers.

ACQAO UQ staff lead by Dr Joel Corney held Siemen's Science Experience Workshops over two days for high school students.

Siemen's Science Experience Workshops — Chris Foster (right) uses magnetic levitation to illustrate how ultracold atoms can be trapped

Dr Ken Baldwin and Prof Hans-A. Bachor also continued to promote science more generally through the annual 'Science Meets Parliament" day and personally brought the advances in quantum science to the parliamentarians he met with. Local Parliamentarians and Board members Gary Humphries and Bob McMullan were each later given personal tours of the Centre laboratories.

Prof Peter Drummond and Prof Hans-A. Bachor gave invited presentations on the topic of the 2005 Nobel Prize at the University of Western Australia and the Australian National University.

Prof Hans-A. Bachor was elected to the Board of the National Youth Science forum and contributed to the forum through talks and presentations.

Dr Max Colla

Dr Max Colla (ANU) was regularly interviewed during the year by SBS Italian Radio program on physics and current affairs.

Many members of our Centre attended international conferences. We used these opportunities to present quantum-atom optics to a wider audience, ranging from school classes in Germany (Hans-A. Bachor) to students in the USA (John Close).

Prof Peter Hannaford led a successful bid to host the International Conference on Atomic Physics in Australia in 2010.

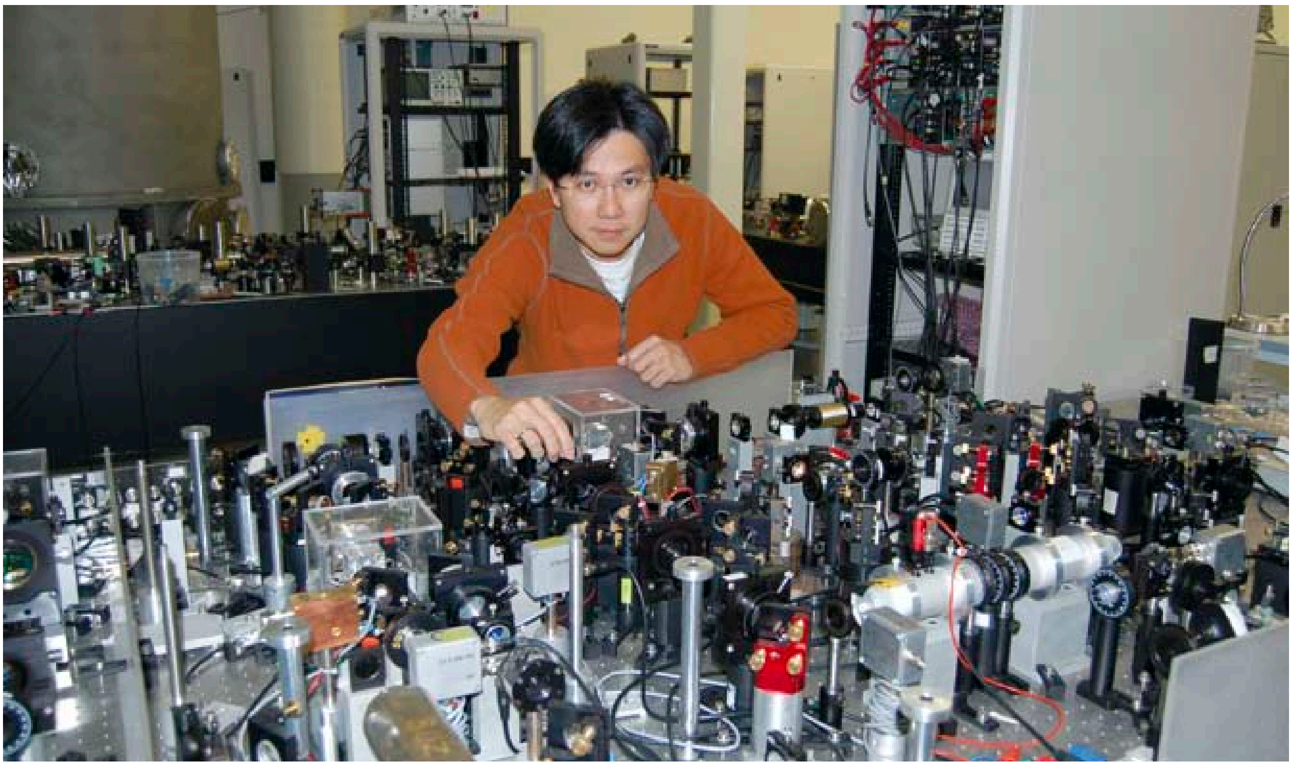
Prof Ping Koy Lam (ANU) (pictured below) received the 2006 Eureka Prize for Scientific Research.

Our Swinburne personnel were recognised by the members of the Editorial Board of Journal of Physics B: Molecular, Atomic and Optical Physics (J Phys B) when they chose the paper "A permanent magnetic film atom chip for Bose-Einstein condensation" Hall et al., J Phys B 39, 27–36 as one of the six highlight full papers to appear in the *J Phys B Highlights of 2006*.

During 2006 Dr Ken Baldwin (ANU) commenced his three year term as member of the Board of Directors of the Optical Society of America, just one of three Directors from outside America and the first ever from Australia.

Dr Brenton Hall (SUT) presented a talk on the work of ACQAO to young scientists in Melbourne while Prof Peter Hannaford (SUT) was invited to talk to the Probus Club in Camberwell on June 7 on the 2005 Nobel Prize in Physics.

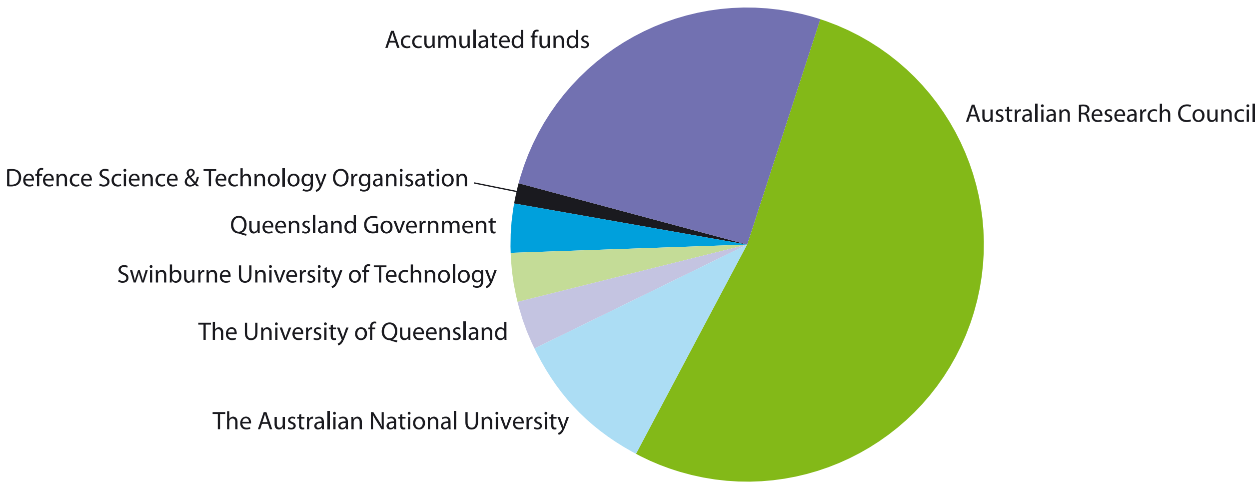
Prof Hans-A. Bachor gave briefings to the German Embassy and German science delegations.



Professor Ping Koy Lam (ANU)

ACQAO INCOME 2006

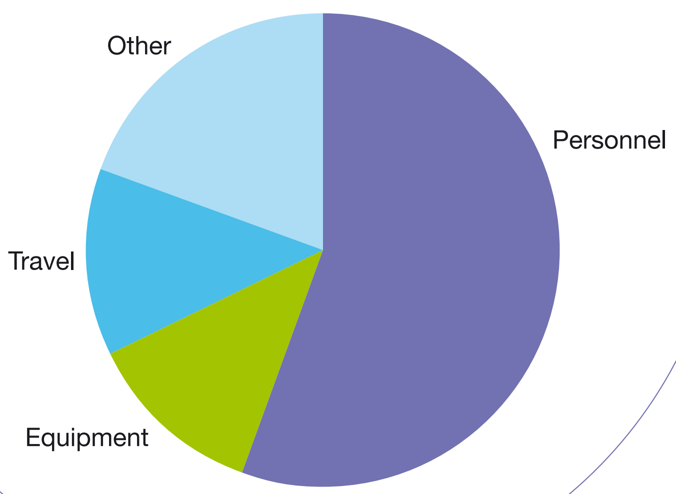
Accumulated funds*	$1,175,761.00
Australian Research Council	$2,386,931.00
The Australian National University	$456,000.00
The University of Queensland	$150,000.00
Swinburne University of Technology	$150,000.00
Queensland Government	$150,000.00
Defence Science & Technology Organisation	$60,000.00
TOTAL	**$4,528,692.00**



* Accumulated 2005 funds adjusted to meet consolidaed Node figures

ACQAO EXPENDITURE 2006

Personnel	$1,928,709.00
Equipment	$423,965.00
Travel	$436,656.00
Other	$668,241.00
TOTAL	**$3,457,571.00**



ACCUMULATED FUNDS **$1,071,121.00**

ACQAO 2006 PERSONNEL

ANU FAC
Prof Hans-A. BACHOR
Dr Ben BUCHLER
Dr John CLOSE
Dr Max COLLA
Mr Neil DEVLIN
Dr Cristina FIGL
Dr Oliver GLOECKL
Dr Charles HARB
Mr Neil HINCHEY
Dr Joe HOPE
Dr Mattias JOHNSSON
Prof Ping Koy LAM
Dr Nick ROBINS
Dr Craig SAVAGE
Ms Ruth WILSON
Dr Hongxin ZOU
Mr Tom ARGUE
Mr Kerry BURKE
Mr Vincent DELAUBERT
Mr Graham DENNIS
Mr Julien DUGUE
Mr Simon HAINE
Mr Gabriel HETET
Mr Magnus HSU
Mr Jiri JANOUSEK
Mr Matthew JEPPESEN
Mr Mikael LASSEN
Ms Sarah MIDGLEY
Mr Daniel OBLAK
Ms Katie PILYPAS
Mr Roger SENIOR
Mr Paul SOMMERS
Mr Oliver TOPIC
Ms Katherine WAGNER
Mr Sebastian WUESTER

ANU IAS
Dr Ken BALDWIN
Dr Tristram ALEXANDER
Mr Steve BATTISSON
Ms Deborah BORDEAU
Dr Robert DALL
Prof Yuri KIVSHAR
Dr Chaohong LEE
Dr Elena OSTROVSKAYA
Dr Andrew TRUSCOTT
Ms Lesa BYRON
Mr Santiago CABALLERO
Ms Beata DABROWSKA
Mr Andre STOFFEL

UQ
Prof Peter DRUMMOND
Dr Ashton BRADLEY
Dr Joel CORNEY
Dr Matthew DAVIS
Ms Stephanie GOLDING
Dr John HEDDITCH
Dr Hui HU
Dr Karen KHERUNTSYAN
Dr Xia LIU
Dr Murray OLSEN
Dr Margaret REID
Mr Clinton ROY
Ms Linda SCHUMACHER
Mr Paul SCHWENN
Mr David BARRY
Mr Eric CAVALCANTI
Mr Andrew FERRIS
Mr Chris FOSTER
Mr Scott HOFFMANN
Mr Kalai Kumar RAJAGOPAL
Mr Andrew SYKES
Mr Tim VAUGHAN

SUT
Prof Peter HANNAFORD
Dr Alexander AKULSHIN
A/Prof Bryan DALTON
Dr Grainne DUFFY
Dr Brenton HALL
Prof Fel Tien KIEU
Mr Mark KIVINEN
Prof Fel Russell MCLEAN
Dr Wayne ROWLANDS
Prof Fel Andrei SIDOROV
Ms Tatiana TCHERNOVA
Dr Michael VOLK
Dr James WANG
Mr Russell ANDERSON
Mr Paul DYKE
Mr Jurgen FUCHS
Mr Saeed GHANBARI
Mr Heath KITSON
Mr Stephen MCDONALD
Mr Blake ORR
Mr Michael PULLEN
Ms Megan ROMEO
Mr Mandip SINGH
Mr Anthony TEEL
Mr Gopisankararao VEERAVALLI
Mr Shannon WHITLOCK
Mr Holger WOLFF

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Australian Research Council Centre of Excellence for Quantum-Atom Optics

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