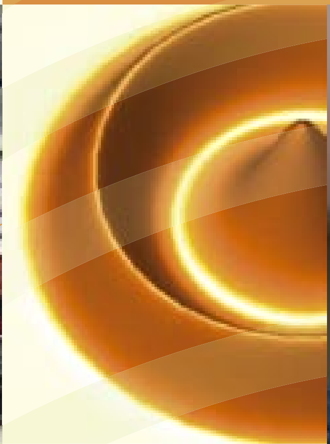

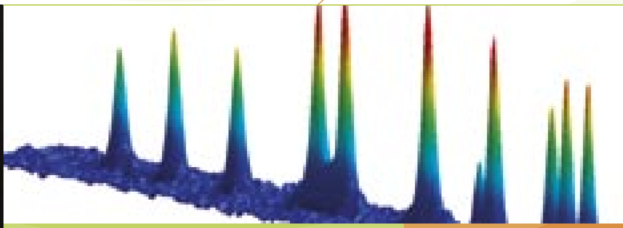

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report for the year 2005

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

SWIN BUR NE
SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian Government
Australian Research Council

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Scientific Reports

FOREWORD

This third year of our Centre has produced many exciting new results, both in theoretical work and in experiments, and our achievements have been acknowledged and praised in the review by the Australian Research Council. We are well on the way to reaching our ambitious goals at a time when quantum and atom optics is expanding as a research topic globally. During 2005 we have increased our impact, both with our scientific peers and with the general public, by showing that quantum science and technology will play a major role in future technology and eventually our daily lives.

The ARC Centre of Excellence for Quantum-Atom Optics (ACQAO) is a key part of Australia's contribution to the rapid development of quantum science that is happening around the world. It concentrates on fundamental science questions and creates scientific tools for the engineers of the future, with a focus on the application of quantum and wave effects to both light and atoms.

Scientifically we are now able to investigate the quantum behaviour of larger objects, involving thousands and even millions of atoms, and see the transition from the microscopic world of a few particles to the macroscopic classical world. Technically we are now able to create entanglement, which was just a concept in the 1930s, and eventually use it in practical applications, such as communication systems. We have the technology for cooling atoms to unimaginably low temperatures and for creating Bose-Einstein condensates (BEC) and atom lasers. Combining these we are at the threshold of turning fundamental science into practical applications over the coming decades.

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. This combination of talent and resources, and their close interaction, ensures that Australia can make major contributions internationally.

Examples of our progress include: two more BEC experiments, using Rubidium atoms on a magnetic chip at SUT, and metastable helium atoms at ANU; from UQ the first exact theory of atom correlations in a one dimensional waveguide, from ANU the description of matter wave solitons and vortices in optical lattices; plus the direct generation of higher order modes of squeezed light, and many other results described in this report.

Our Centre is part of the vision of the ARC to promote excellence in the most successful fields of research and to give them the opportunity to become major players in the international arena. We have established and extended close research partnerships with five institutions in Europe and two in New Zealand. The funding and support provided by the ARC, the three Universities (ANU, UQ and SUT), the state governments of Queensland and the ACT, and from DSTO allows us to tackle ambitious parallel research projects, to create an intensive exchange of staff and students, to provide opportunities for young scientists and to reach out into the community.

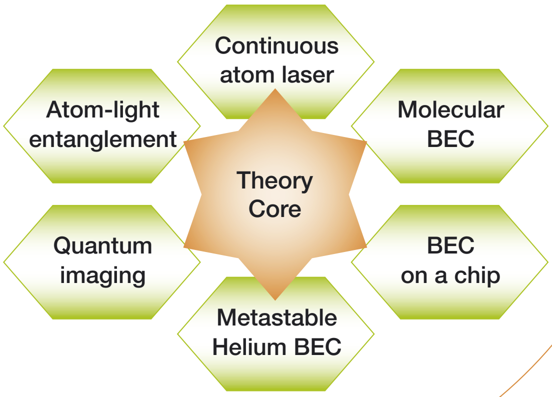
This, our third annual report, describes the structure of the Centre, the staff, our research plans and our achievements in 2005. You will learn about our major advances in all our experiments, and from our theory teams, in the new science reports. We are accelerating in our progress towards the original goals of the Centre, all of which remain valid in the international scientific context.

I hope this report gives you an insight into this exciting and stimulating venture that will enable the quantum technologies of the future.

Hans-A. Bachor

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 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 until now is essentially based on classical optics, will benefit soon from the advances in quantum optics.

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

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.

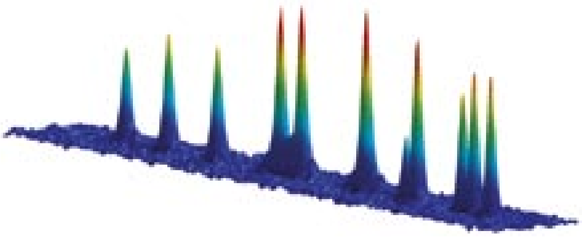
For example, these could be two laser beams, propagating into different directions created in one source and which contain identical information, modulation and noise. Or they could be two, or more, beams of particles which have identical properties. Some of the pioneering theory work was done in Australia and the extension to systems of many particles 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 22).

Atom Optics

Atom optics, by comparison, is a field where we find that atoms not only have the properties of particles that move and collide with each other, but also have properties which require a wave description. 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 interfere. This is now experimentally possible and allows whole new types of precision instruments, namely atom interferometers.

These can be developed into very sensitive sensors, for example, for measurements of the gravitational field. In addition the bosonic atoms such as Rb87, Cs133, He* will make a rapid transition into a new state of matter once they cool below a critical temperature. This is a so-called Bose-Einstein Condensate (BEC) that has properties vastly different from a cloud of atoms.



Multiple BECs generated in the SUT laboratory

Different BECs for new science

By the end of 2005, Australia has four BECs, three in Rb and one in metastable Helium, all optimised for different studies and applications. Three are part of ACQAO and are used to further develop the technology to make the apparatus more reliable and all 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 11).

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 high accuracy. We can now generate multiple BECs on the chip that allow us to study the interference of matter waves in great detail.

In addition, we are extending the work in Europe by generating a BEC from metastable Helium (He*) atoms. This machine operates very reliably (page 7) 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 also propose to extend the generation of a BEC from atoms to molecules. More results were recently reported in Europe and the USA on generating and condensing molecules. We wish to demonstrate some of the novel correlation effects, predicted in theories created by members of our Centre.

Atom Laser

An extension of the BEC work is to create an atom laser, a device that produces a coherent beam of atoms, in analogy to an optical laser. In 2005 we showed the operation of our atom laser in the quasi-continuous regime and made the first measurements on noise and flux in this system. This knowledge is critical for the development of practical devices and applications.

We have made initial studies of the first continuous Raman out-coupled atom laser, which allows us to investigate the flux limitations of the atom laser and to systematically improve its performance.

In parallel special diagnostic techniques are being developed to demonstrate the unique quantum properties of a source of matter waves. We have developed the theory for an atom laser that would produce a pair of entangled atom beams (page 17).

Linking Quantum and Atom Optics

This Centre combines, in a unique way, quantum optics and atom optics, theory and experiments. A key project is to build an apparatus that can transfer the entanglement from the light to atoms and vice versa. This would be an initial step in designing storage for quantum information. During 2005 we made progress with delaying information and investigating the additional noise introduced by the atoms. Related experiments on quantum information, communication and cryptography are carried out independently at the ANU and in collaboration with other Centres of Excellence.

Theory points the way

All these experimental goals are guided 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 is the range of new ideas and techniques developed at UQ to simulate the properties of Fermions from first principles (page 24) which leads to experiments at SUT. Another is the first exact theory of atom correlations in low dimensions (page 9) that has 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 30) 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 in quantum and atom optics, by linking the leading scientists in Australia and by developing an exchange with our partners in Europe, who are in some of the most productive groups in this field. In this way the Centre is present in the international arena and ensures that future optical quantum technology will remain accessible to Australia.

THE NODES — STRUCTURE OF THE CENTRE

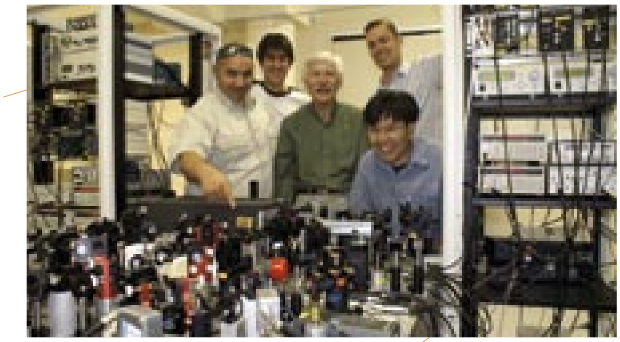
The Centre combines many of the leading scientists in quantum and atom optics in Australia. They and their laboratories are thriving in three locations: Canberra, Melbourne and Brisbane, and are linked through joint scientific projects, the sharing of expertise and equipment and the exchange of people. We have formed research teams spanning several nodes. The scientific goals have been chosen to be ambitious; they 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 2005 we have a total staff of 37 plus 28 students.

ANU FAC, Canberra

L to R: Katie Pilypas, Gabriel Hetet, Charles Harb, Magnus Hsu, Olivier Gloeckl in the ACQAO lab at ANU Faculties

At the ANU our research node carries out experimental work with the Rb BEC and atom laser, including the development of new minimally destructive 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 (Ping Koy Lam, Oliver Gloeckl).



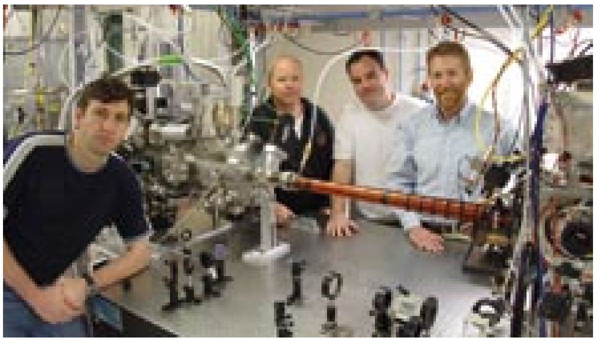
Charles Harb, Vincent Delaubert, Hans-A. Bachor, Mikael Lassen and Ping Koy Lam

This is complemented by novel 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.

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 IAS, Canberra

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



L to R: Robert Dall, Steve Battisson, Andrew Truscott, Ken Baldwin

and soliton physics (Yuri Kivshar, Elena Ostrovskaya, Tristram Alexander, Chaohong Lee) and their focus is the properties of matter waves in optical lattices.

Back row L to R: Andre Stoffel, Santiago Benitez Caballero, Chaohong Lee
Front row L to R: Beata Dabrowska, Elena Ostrovskaya, Yuri Kivshar, Miklos Gulacsi

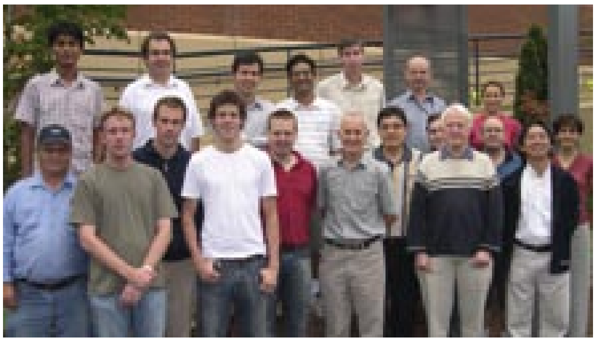
UNIVERSITY OF QUEENSLAND, Brisbane

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, Joel Corney, Matthew Davis, Karen Kheruntsyan, Murray Olsen, Hui Hu, Xia-Ji Li, Ashton Bradley 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.

Standing back row L to R: Andy Ferris, Murray Olsen, Scott Hoffmann, Matt Davis
Middle row L to R: Chris Foster, Paul Schwenn, Margaret Reid, Karen Kheruntsyan, Clinton Roy, Ashton Bradley, Hui Hu
Sitting front row L to R: Tim Vaughan, Linda Schumacher, Peter Drummond, Xia-Ji Liu, Joel Corney

SWINBURNE UNIVERSITY OF TECHNOLOGY, Melbourne

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 unique Rb BECs on a chip (Andrei Sidorov, Russell McLean, Brenton Hall, Peter Hannaford). In parallel, an experiment for the generation and condensation of Lithium-6 molecules is in progress (Wayne Rowlands, Grainne Duffy, Peter Hannaford). A small theory group complements this work (Bryan Dalton, Tien Kieu).



Back row L to R: Mandip Singh, Andrei Sidorov, Saeed Ghanbari, Gopisankararao Veeravalli, Russell McLean, Alexander Alkulshin, Grainne Duffy
Front row L to R: Mark Kivinen, Paul Dyke, Heath Kitson, Jurgen Fuchs, Holger Wolff, Peter Hannaford, James Wang, Shannon Whitlock, Bryan Dalton, Brenton Hall, Tien Kieu, Tatiana Tchernova.

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 52. The administration includes research assistant Max Colla (ANU FAC) and Administrators Linda Schumacher (UQ), Sharon Jesson/Tatiana Tchernova (SUT) and 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 the financial administration and all operational aspects. The fundamental decisions in the Centre are determined by all Chief Investigators together.

This is achieved in bi-annual CI meetings (Melbourne 4/2005, Queenstown New Zealand 12/2005). 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 and regular science meetings are held fortnightly within the nodes. 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.

Advisory Board Members L to R: Eugene Polzik (Denmark), Alain Aspect (France), Bill Phillips (USA)

The Centre organises scientific workshops, planning sessions and discussions which bring together members of the Centre from all locations. During 2005 we prepared a submission to the ARC review, which highlighted our achievements and goals. The Review visit was held in October and we are pleased to have received positive recommendations.

We are fortunate to have an Advisory Board of outstanding expertise. Our international science advisors are leaders in the field and highly distinguished scientists. They have visited us twice and provide us with detailed scientific advice for all aspects of the Centre. 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 Institut Copenhagen,
Denmark
Prof David Pegg, Griffith University Brisbane,
Australia.

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

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

Centre Management Meetings			
CI meeting	All CIs & COO	Bi-annual	15/4 Melbourne 1/12 Queenstown
Executive Board	Res Dir. & COO Node Directors	Quarterly	5/4 Canberra 7/7 Canberra 10/8 Melbourne
Advisory Board	International & national members	Annually	Scheduled for February 2006
International Workshop	Centre & partners, other AUS groups	Bi-annual	28 November – 2 December Queenstown
Individual Project & group	Staff & students, visitors	Fortnightly	
IP committee	Node directors, Universities	Annually	24/9 Canberra

Bose Einstein Condensation of Metastable Helium

R. G. Dall, K. G. H. Baldwin and A. G. Truscott
ACQAO, Research School of Physical Sciences and Engineering,
The Australian National University, Australia.

The main goal of our research is to study the evolution of relative phase between two Bose Einstein condensates (BEC). In particular, we would like to answer some fundamental questions about the phase of a BEC. Do two well separated BECs have an intrinsic relative phase? Or does the act of measuring atoms released from the condensates impose a relative phase on them? At what stage in the measurement of the phase is the interference pattern established?

To answer these questions 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 BECs 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. In our experiment we load around 5x10^8 atoms into a high vacuum magneto-optic trap (MOT) from a low velocity intense atomic beam (LVIS) of He* [3]. To transfer atoms into our magnetic trap we first spatially compress the MOT, by tuning the MOT laser frequency closer to resonance. Following compression the atoms are further cooled to around 200 μK by applying a 3-D Doppler molasses stage at which point the magnetic trap is energised with a bias field of 20 Gauss. In such a configuration the trap has very weak trapping frequencies, typically $f_r = 84Hz$ and $f_a = 75Hz$, which minimises heating of the atomic cloud. At transfer we have around 3x10^8 atoms at a temperature of 600 μK. Immediately after transfer we apply a laser beam along the bias field of the magnetic trap, polarised such that atoms cycle back to the low field seeking trapping state. This laser beam is detuned $\sim -\Gamma/2$ from the m$_f$= 1 $\rightarrow$ m$_f$= 2 transition and cools the atoms down to $\sim$ 150 μK. The bias field of the trap is then reduced to 5 Gauss, increasing confinement and subsequently increasing the temperature of the gas. To remove this heat we apply a second Doppler cooling stage, once again achieving a temperature around $\sim$ 150 μK. At this point, we have excellent starting conditions to achieve runaway evaporation. We evaporate in six seconds using a trajectory comprising seven linear stages. We reach the transition temperature at $\sim$ 1 μK with around one million atoms.

In the coming year we plan to probe the quantum statistical nature of our BEC.

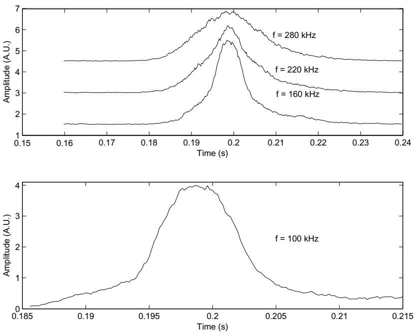


Figure 1: Demonstration of BEC. Time of flight traces taken from an electron multiplier located directly under our magnetic trap. Traces are shown for runs of the experiment with different final evaporation frequencies. As the cloud is cooled down, a bimodal distribution is seen indicating the presence of a BEC.

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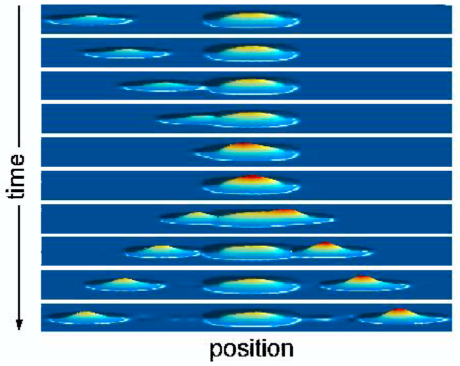
Atomic-molecular Bose-Einstein condensates

K. V. Kheruntsyan, M. K. Olsen, and P. D. Drummond
ACQAO, School of Physical Sciences, University of Queensland, QLD 4072, Australia

The study of coupled atomic-molecular Bose-Einstein condensates is currently an active research topic in the field of ultracold quantum gases. Our calculations here are potentially relevant to future Rubidium dimer experiments that could be carried out at either the SUT or ANU nodes of ACQAO. We also aim to model recent experiments on dissociation of $^{87}Rb_2$ dimers in the group of G. Rempe at the Max Planck Institute for Quantum Optics, Garching, Germany [1]. We have made progress as follows:

1. We have studied a scheme for parametric amplification of a (small) atomic BEC via stimulated dissociation of a BEC of molecular dimers in a 1D geometry [2]. This can be realized using a magnetic Feshbach resonance or optical Raman transitions, and is shown to produce number-correlated atomic beams – the amplified beam and its phase-conjugate replica – propagating in opposite directions.



Snapshots of a quantum dynamical simulation of this process are shown in the figure, where we plot the density profiles of the atomic and molecular (shown in the middle) clouds. The resulting two output beams are strongly correlated in the particle number and have squeezed number-difference fluctuations. The squeezing with a mesoscopic total number of atoms can be achieved on much shorter time scales than in spontaneous dissociation [3], which makes the present scheme more feasible for practical implementation, using typically short-lived molecular condensates.

2. We have published a Reply to “Comment on ‘Stimulated Raman adiabatic passage from an atomic to a molecular Bose-Einstein condensate’” [4]. In the Comment [5], the authors suggest that the molecular conversion efficiency in atom-molecule STIRAP can be improved by lowering the initial atomic density, which in turn requires longer pulse durations to maintain adiabaticity. In our Reply [4], we point out that a low-density strategy with longer pulses has several problems. It generally requires higher pulse energies, and increases radiative losses. We show that even within the approximations used in the Comment, a more careful analysis reveals that the increased radiative losses and longer pulse durations lead to almost no conversion.

3. We have put forward a theoretical proposal [6] of a test of local realism with mesoscopic numbers of massive particles. Using dissociation of a BEC of homonuclear diatomic molecules into bosonic atoms, we demonstrate that strongly entangled atomic beams may be produced which possess nonlocal Einstein-Podolsky-Rosen (EPR) correlations in particular field quadratures. These are directly analogous to the position and momentum correlations originally considered by EPR.

4. We have begun 3D quantum dynamical simulations of dissociation of a molecular BEC into bosonic atoms. This is aimed at quantitative modelling of atom correlation measurements via time-of-flight absorption imaging. Further details are included in a separate report “Correlations between bosonic atoms dissociated from a BEC of molecular dimers”.

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Low dimensional quantum gases

K. V. Kheruntsyan, Xia-Ji Liu, H. Hu, and P. D. Drummond
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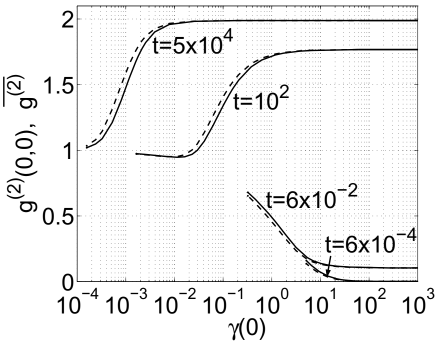
Low-dimensional quantum gases represent examples of strongly correlated quantum systems and are the subject of intense theoretical and experimental activity in many areas of physics. These are relevant to the ACQAO experimental programs in the areas of interferometry in atom chips with Bose or Fermi gases (SUT), as well as to future atom-counting experiments with metastable Helium (ANU).

In 2005, we have made further progress in the studies of atom correlations in one-dimensional (1D) Bose gases [1]. We have calculated the density profiles and density correlation functions of a harmonically trapped (nonuniform) 1D Bose gas, using the exact finite-temperature solutions for the uniform case and applying a local density approximation. The results are valid for a trapping potential which is slowly varying relative to a correlation length. They allow a direct experimental test of the transition from the weak coupling Gross-Pitaevskii regime to the strong coupling, "fermionic" Tonks-Girardeau regime. We have also computed the average two-particle correlation $\overline{g^{(2)}}$ which characterizes the bulk properties of the sample, and found that it can be well approximated by the more readily calculated local pair correlation in the trap center, $g^{(2)}(0,0)$.



The figure on the left shows $g^{(2)}(0,0)$ (solid lines) and $\overline{g^{(2)}}$ (dashed lines) as a function of the interaction parameter $\gamma(0)$, for four different values of a dimensionless temperature parameter t. This result is of practical importance as it gives a direct justification of the analysis performed in [2] where the results of the measurements in a bulk nonuniform sample have been compared with theoretical predictions for the local pair correlation in a uniform gas [3]. More recent experiments in D. Weiss's group [4] are also in excellent agreement with our theoretical results.

In addition, in view of the rapid growth in ultra-cold fermion physics, we have commenced a program of investigating the signature of the fermionic Mott-insulator transition in a 1D optical lattice [5]. With optical lattices, a harmonic potential is necessary to prevent the atoms from escaping, so that the Mott-insulator phase is restricted to an insulator domain at the center of the trap, and coexists with two compressible metallic wings. In this work, we show that collective oscillations of the atomic mass density, an indicator of compressibility, can be utilized to monitor the emergence of the Mott-insulator phase. We consider a zero temperature, one-dimensional Hubbard model with a harmonic potential, as a model of an ultra-cold two-component fermionic atomic cloud in a deep optical lattice with strong radial and weak axial confinement. Based on the exact solution of the homogeneous 1D Hubbard model, together with the local density approximation, we calculate the density profile of the cloud as functions of a characteristic filling factor and coupling constant. This leads to a generic phase diagram including a metallic phase and a Mott-insulator phase. We then investigate the low-energy collective density oscillations of the cloud in different phases using Luttinger liquid theory, which describes long wavelength hydrodynamic behaviour. We predict a sharp dip in all collective mode frequencies in the vicinity of the phase boundary, giving a clear signature of the Mott metal-insulator transition.

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Collapsing BECs beyond the Gross-Pitaevskii approximation

S. Wüster[1], J. Hope[1], M. Davis[2] and C. Savage[1]
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We have analysed one of the more straightforward aspects of the JILA bosenova experiment [1]: the time to collapse. It has previously been shown that the Gross-Pitaevskii (GP) theory sometimes substantially overestimates these collapse times [2]. We have found that adding the lowest order quantum field corrections does not improve the situation much [3]. Thus an open question remains: what explains the discrepancy between theory and experiment?

To go beyond mean field theory we start from the usual Hamiltonian for a many body system that interacts by a contact potential. $\hat{\Psi}_a(\mathbf{x}, t)$ denotes the field operator that annihilates an atom at position $\mathbf{x}$. We derive the Heisenberg equation for the field operator, and subsequently decompose it into a condensate part $\phi_a(\mathbf{x}, t)$ and quantum fluctuations $\hat{\chi}(\mathbf{x}, t)$, such that $\hat{\Psi}_a = \phi_a + \hat{\chi}$ and $\langle\hat{\Psi}\rangle = \phi_a$. We describe the fluctuations in terms of their lowest order correlation functions: the normal density $G_N(\mathbf{x}, \mathbf{x}') = \langle\hat{\chi}^\dagger(\mathbf{x}')\hat{\chi}(\mathbf{x})\rangle$ and anomalous density $G_A(\mathbf{x}, \mathbf{x}') = \langle\hat{\chi}(\mathbf{x}')\hat{\chi}(\mathbf{x})\rangle$. In deriving the dynamical equation for the condensate we factor the expectation values in accordance with Wick's theorem. The resulting equations are known as the Hartee-Fock-Bogoliubov (HFB) equations.

While the GP equation can be tackled even in a completely asymmetric geometry, doing so for the HFB equations, even with cylindrical symmetry, would present a serious numerical problem, since the dimensionality of the correlation functions would only reduce from six to five. The requirements for memory and computation time would exceed those for spherical geometry by two orders of magnitude. We are therefore forced to use a spherically symmetric numerical model.

We found that the BEC does not collapse earlier than in the corresponding spherical GP simulations. The number of atoms in excited modes does not grow fast enough to accelerate the collapse, although just before the anticipated collapse point large numbers of uncondensed atoms are created. We also checked that the inclusion of the molecular field, and thus an energy dependent description of scattering properties, does not change the result.

A drawback of the HFB method is that the interaction between uncondensed and condensed atoms is not properly renormalized [4]. However the effects of renormalization on the coupling constant are small and it is not expected that a more complete renormalization would significantly alter the number of uncondensed atoms.

We are using the classical field techniques developed at the University of Queensland to perform quantum simulations of the collapsing BECs. Trajectories in the truncated Wigner phase space method obey the GP equation but with additional noise to take quantum effects into account.

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Bose-Einstein Condensation in a Permanent Magnetic Microtrap on a Chip

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Microfabricated circuits on a surface produce tightly confining, purpose-tailored, magnetic potentials that can be used as networks of microtraps, waveguides and beamsplitters for ultracold atoms (atom chips). The miniaturisation of components greatly simplifies the creation of Bose-Einstein Condensates (BECs). The Swinburne atom chip combines a perpendicularly magnetised film (TbGdFeCo) with current-carrying wires for the production and manipulation of BECs. The two technologies allow greater flexibility in the quantum control of matter waves.

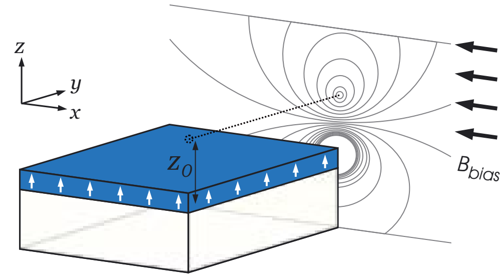

Fig. 1. A combination of a magnetic field from a perpendicularly magnetised film and a bias field produces a radially symmetric two-dimensional waveguide above the surface. The strength of the radial confinement and the location of the waveguide are determined by the value of the bias magnetic field.

A current-carrying conductor on the chip is initially used for laser cooling and compression of the atomic cloud. A magnetic trap located 560 μm from the surface is also employed for preliminary RF cooling of rubidium-87 atoms to a temperature of $\sim 5\ \mu$K. The atoms are then transferred to a magnetic film microtrap 90 μm from the surface (Fig. 1) and evaporatively cooled for 1 s to the BEC phase transition (Fig. 2). The atom chip creates a new condensate of around 10^5 atoms in the magnetic film trap every 50 s [1].

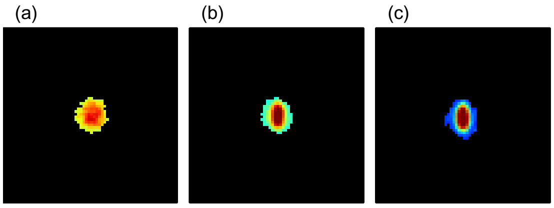

Fig. 2. Absorption images of an atomic cloud, released from a magnetic film trap, after 30 ms of ballistic expansion. The images were taken at different stages of evaporative cooling and correspond to: (a) a thermal cloud (Gaussian distribution), (b) a partially condensed cloud (bi-modal distribution corresponding to the onset of BEC), (c) a pure condensate.

The radial potential of the magnetic film trap has been characterised by observing centre of mass oscillations of the trapped atoms. Harmonic oscillations with small amplitude were monitored over many periods. By exciting centre of mass motion the frequency of the radial oscillations ($\sim$ 1 kHz) can be measured to better than 1 Hz accuracy due to low damping rates and small spatial extent. The value of the trap frequency in combination with the trap bottom potential unambiguously determines the local magnetic field gradient. The frequency and the position have been measured against different values of an applied bias magnetic field. The data are consistent with the prediction of a simple model of a perpendicularly magnetised film (Fig. 1).

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Multiple Bose-Einstein Condensates in a Disordered Potential on a Chip

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Clouds of ultracold atoms have a small spatial extent and a narrow energy distribution and can be used as a highly sensitive magnetic field microprobe. The trapped atoms are centred in the local minimum of a magnetic field and the atomic density decreases with the rise of the potential. Thus the spatially variable atomic density is a measure of the magnetic field landscape. RF-induced spin-flips remove atoms at a position where the Zeeman splitting is equal to the RF energy. Using RF spectroscopy we have mapped small spatial variations of the magnetic field close to the edge of the film (Fig. 1).

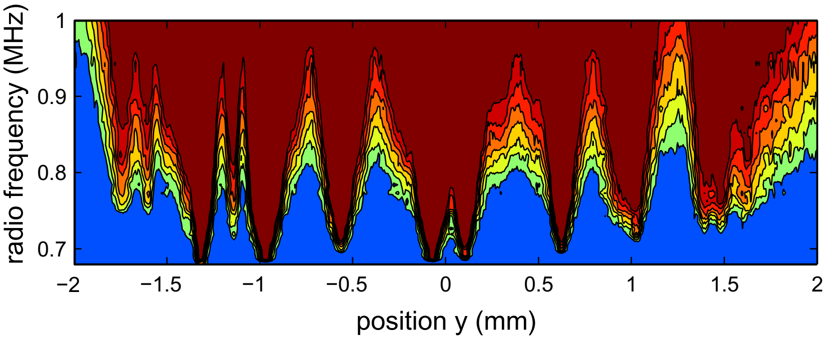

Fig. 1. Contour plot of the atomic optical density measured at a height of 87 μm above the film and plotted as a function of the radio frequency and position along the magnetic film.

A spatially oscillating aperiodic component of the trapping potential leads to fragmentation of the cold cloud close to the film. The amplitude of the disordered potential increases when the atoms approach the film. Evaporative cooling of a highly elongated thermal cloud (extension $\sim$ 5 mm) close to the surface leads to the situation where the BEC phase transition is reached simultaneously across 11 independent potential wells spanning 3 mm [1] (Fig. 2).

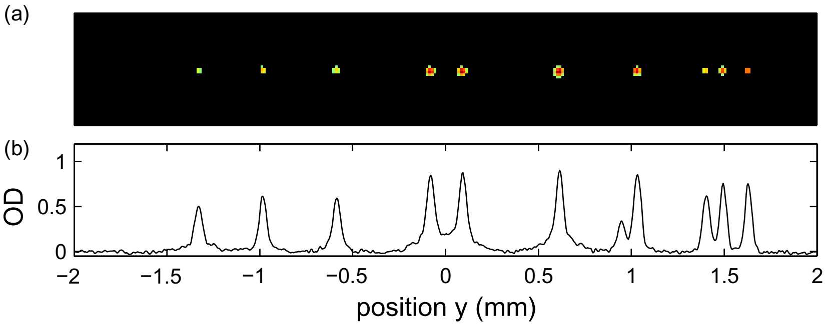

Fig. 2. (a) A string of Bose-Einstein condensates in the disordered potential created by the magnetic film. An absorption image is recorded after 15 ms of ballistic expansion. (b) Density profiles taken along the axis of the BEC string.

Disordered potentials are attractive for studies of the interference of matter waves and of the wave transport in random systems. We have carried out preliminary experiments on the splitting of a BEC in a double-well magnetic potential present near the centre of Fig. 1. A single BEC is created 170 μm from the surface where the fragmentation is small. By increasing the bias magnetic field we carefully move the condensate closer to the surface where it splits into two parts. The two BECs were separated by up to 140 μm. The current resolution of our imaging system did not permit the observation of interference fringes that would be present in ballistic expansion.

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’Shut down’ of a continuous atom laser

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The atom laser is the atomic analog of an optical laser. A Bose-Einstein condensate (BEC) is used as a reservoir of atoms, from which a coherent output coupling mechanism converts atoms from trapped to untrapped states. In this work we investigate the crossover from weak to strong output-coupling in a continuous atom laser based on a radio-frequency (RF) mechanism [1]. Our previous experiments on a pulsed output-coupler suggested that a continuous atom laser would have a stringent limit on peak homogeneous flux [2]. Here we show that peak flux into the magnetic field insensitive state is indeed significantly below that which can be provided by the finite reservoir of BEC atoms that we produce. This ’homogeneous flux’ limit is imposed by the interaction between multiple internal Zeeman states of the magnetically confined atoms. Furthermore, we find that a previously predicted effect known as the ’bound state’ of an atom laser, effectively shuts off state changing output-coupling and hence the atom laser beam.

The experimental data presented in Figure 1 encapsulate the main results of our work. The figure shows the densities of the condensate and atom laser beam in a series of experiments with a 3 ms continuous atom laser, produced in the F=2 manifold of ^{87}Rb by state changing output coupling to a magnetic field insensitive state. At low output-coupling strength the atom laser beam flux increases gradually and homogeneously until the angular Rabi frequency is approximately 1 kHz. At around this value we observe that the anti-trapped $\mathrm{m_F}$=-2,-1 states begin to play a part in the atom laser dynamics. This leads to increasingly severe fluctuations in the density of the atom laser beam, and a loss of atoms to the anti-trapped states (Fig 1(a),(b)). A further increase in the coupling strength incrementally shuts down the output starting around 4 kHz . In the limit of large output coupling strength we find approximately 70% of the atoms remain localized in the condensate, while the other 30% are emitted shortly after the beginning of the output coupling period (Fig 1(c)).

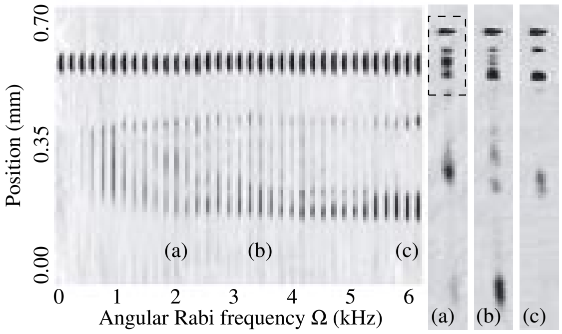

Figure 1: Optical depth plot (35 independent experiments) showing the spatial structure of a 3 ms atom laser as a function of output-coupling strength parameterised by the Rabi frequency. The system was left to evolve for a further 4 ms before the trap was switched off and 2 ms later the images were acquired. The field of view for each individual image is 0.7 mm by 0.3 mm. Gravity is downwards in these images. Anti-trapped Zeeman states are clearly visible in (a), (b), and (c) which show an extended view of the data (2.7 mm by 0.3 mm). The dashed line in (a) indicates the field of view for each image in the main part of the figure.

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A continuous Raman atom laser

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In precision measurement applications, atom lasers have the potential to outperform optical lasers and non-optical techniques by many orders of magnitude provided we can increase their flux, and achieve shot noise limited operation at least in some frequency band. To produce an atom laser, a Bose-Einstein condensate (BEC) is used as a quantum degenerate reservoir of atoms, from which a coherent output coupling mechanism converts atoms from trapped to untrapped states. Due to gravitational acceleration the output coupled atoms form a quasi-collimated beam, with the divergence determined by the repulsive interactions between the condensate and atomic beam. The majority of atom lasers experiments have used a radio frequency (RF) mechanism to produce the beam. However, we have recently found that this type of output-coupler is not suitable for the production of a high flux continuous atom laser [1].

Here we report on the production of the first continuous atom laser based on multi-photon Raman transitions (Fig1(b)). This system has the potential to surpass the output flux achievable in an RF atom laser by more than an order of magnitude, because of the large momentum kick imparted by the Raman lasers (up to $4\hbar\mathrm{k}$ or a velocity of $\sim 2.35\mathrm{cm/s}$). In contrast to the *pulsed* Raman atom laser [2], the output beam in our system is homogeneous, in a single Zeeman state ($\mathrm{m_F} = 0$) and has an energy linewidth at least 3 orders of magnitude narrower.

Briefly, our experimental setup is as follows. A single beam from a 70mW diode laser is split and sent through two separate, phase locked AOMs which have a frequency difference corresponding to the Zeeman plus kinetic energy difference between the initial and final states of the multi-photon Raman transition (Fig1(c)). The beams are then coupled via a single mode, polarization maintaining optical fiber, directly to the BEC through a collimating lens and $\lambda/2$ plate, providing a maximum power of 250 $\mathrm{mW/cm^2}$ per beam. The beams are alligned parallel to the weak axis of the magnetic trap and separated by 45 degrees in the vertical direction (Fig1(a)). With the laser polarizations chosen appropriately atoms acquire a momentum kick of $4\hbar\mathrm{k}\sin(45)$ downwards. We are currently pursuing quantitative studies of flux and fluctuations in this type of atom laser output-coupler.

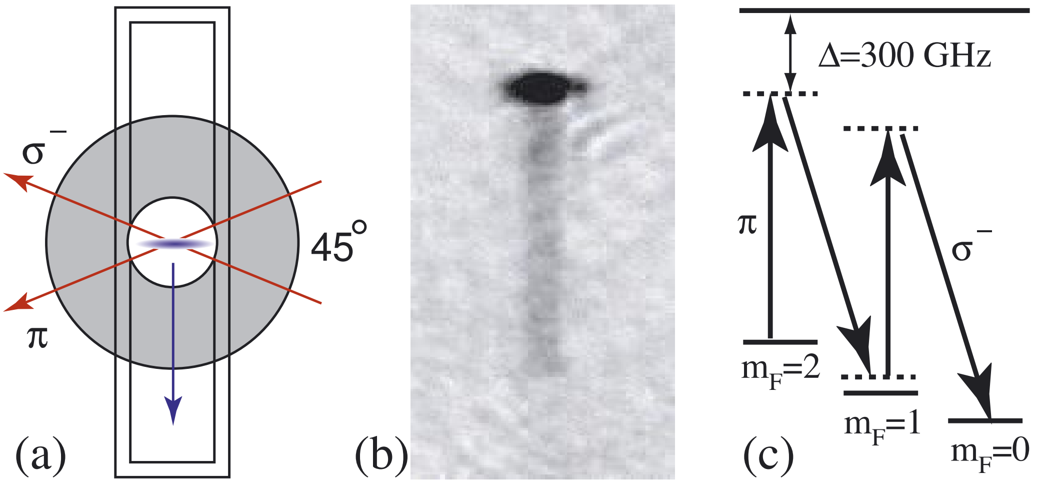

Figure 1. (a) Schematic diagram of the optical set up used for creating the Raman transitions, (b) Absorption image of an 8.5 ms continuous Raman atom laser produced with 40μW per beam, and (c) Transitions from the $5^2\mathrm{S}_{\frac{1}{2}}\mathrm{F} = 2, \mathrm{m_F} = 2$ state to the $\mathrm{F} = 2, \mathrm{m_F} = 0$ state via the $5^2\mathrm{P}_{\frac{3}{2}}$ transition of $^{87}\mathrm{Rb}$.

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Towards a pumped atom laser

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We report on progress towards producing a *continuous atom laser*. Atom laser beams show great promise for use in precision measurements and in studies of fundamental physics. 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. Our first measurements will be a rate equation study of the relative population in each of the condensate, atom laser beam and 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 producing large ^{87}Rb BECs. 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. We are nearing completion of a 'debugging' stage in which all components have been tested, characterised, and brought into operation. We expect to produce condensates in the near future. Current specifications on the machine are a UHV 3D-MOT loading rate of 1×10^9 atoms/s from the 2D-MOT and a total number of 2×10^{10} atoms. Following polarisation gradient cooling, magnetic transport and evaporative cooling, we hope to achieve pure condensates of greater than one million atoms.

A future upgrade of laser power will bring the machine to its full specifications. In this configuration, we expect to increase our 3D-MOT loading rate and total number by at least one order of magnitude.

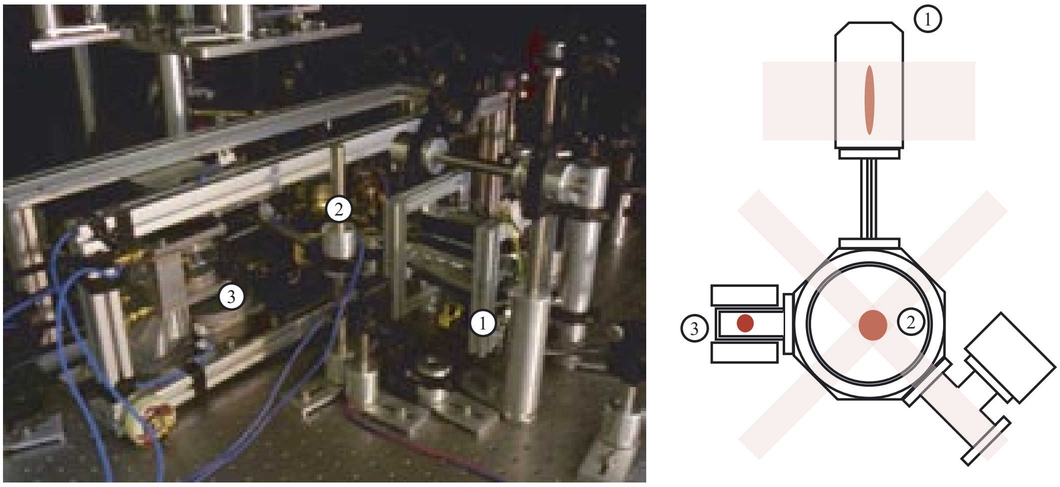

Figure 1: Image and Schematic drawing of the new atom laser machine, showing the 2D-MOT (1), UHV 3D-MOT (2), and UHV QUIC trap (3).

The fundamental quantum limit to the linewidth of an atom laser

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An optical laser has many desirable properties: high flux, very narrow energy spread, specific coherence properties and low divergence. Although atom lasers have interferometric properties that optical lasers do not, we have previously shown that there are more stringent limits to their flux. One of the most fundamental properties of the optical laser is its linewidth, since this is responsible for many of the properties such as first order coherence and high mode occupation number which make the laser a superior optical source. Due to the potential for spatial and non-linear effects, the behaviour and limiting factors to atom laser linewidths are not fully understood. We are studying this problem in preparation for an experimental characterisation of atom laser linewidth.

Fourier analysis requires that a lower limit on the linewidth of an atom laser is the reciprocal of the outcoupling time. Since continuous, pumped atom lasers are not yet available, the outcoupling time has an upper bound given by the drain time of the condensate, which in turn is bounded by the condensate lifetime. While this provides a lower limit for the linewidth, it cannot be a good approximation for the actual linewidth in all parameter regimes; one cannot outcouple for arbitrarily long periods of time and obtain a vanishingly small linewidth. There must be a fundamental quantum limit to the linewidth due to effects such as number fluctuations in the condensate being translated into energy fluctuations. As this effect depends on the quantum statistical properties of the system, a standard semiclassical simulation using the Gross-Pitaevskii equation cannot provide any insight. We have performed single mode analysis of this phenomenon in various limits, but spatial effects will dominant for strong outcoupling and nonlinearities, and cannot be ignored.

We have applied stochastic methods to the problem, allowing us to examine the effects of quantum fluctuations on the linewidth of the outcoupled beam. Our approach has been to use the truncated Wigner method, which is tractable even in the presence of large interaction strengths. We have conducted simulations modelling the use of a Raman scheme to outcouple atoms from a trapped condensate into an untrapped beam, and extracted the linewidth of the beam. One example is shown in Figure 1. The linewidth obtained corresponds to a value of 22 Hz, which is substantially greater than the linewidth of 9 Hz expected from Fourier arguments. This demonstrates that the linewidth is limited by quantum statistical effects in this case.

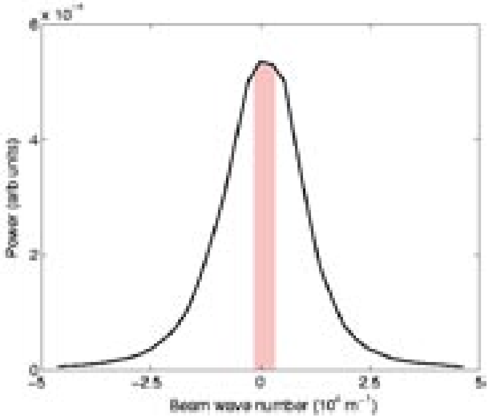

Figure 1: Example spectral output of an atom laser beam calculated using a one-dimensional stochastic simulation with 1024 paths. The line is much broader than the Fourier limit (shown by the shaded region), due to the large interactions.

In the Thomas-Fermi limit, in one dimension, the energy spread in a condensate due to number fluctuation is given by

$$\Delta E = \frac{2m\omega^2 N^{1/6}}{3}\left(\frac{6\pi\hbar^2 a}{m^2\omega^2}\right)^{2/3} . \qquad (1)$$

The true energy width of the beam from our simulations is about one fifth of this prediction, but exhibits the same functional dependence on the parameters. Consequently we are now able to predict the fundamental linewidth limit of a true three-dimensional atom laser, as well as how it scales with experimental parameters.

The Squeezed Atom Laser

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Certain precision measurements are improved by using slow-moving massive particles. In a Sagnac interferometer, for example, the inherent sensitivity of a matter-wave gyroscope exceeds that of a photon gyroscope with the same particle flux and area by 11 orders of magnitude. Although current atom laser experiments operate in a regime limited by technical noise, the fundamental limit of these measurements will be caused by shot noise. Sensitivity is increased in optical interferometers by squeezing the quantum state of the optical field, where the quantum fluctuations in one quadrature are reduced compared to a coherent state. Sensitivity of an atomic interferometer could be increased by using an atom laser with a squeezed output.

We have theoretically investigated the possibility of creating and atom laser with a squeezed output by outcoupling with squeezed light. We have developed a multi-mode quantum field model of a realistic atom laser that takes into account the quantum nature of the optical and atomic fields, and the details of the outcoupling process. We have shown that under appropriate conditions, using a Raman transition to outcouple atoms from a BEC, it is possible to transfer transfer the quantum statistics of an arbitrary optical state from one of the optical beams to the atom laser beam with almost unit fidelity [1].

We have also shown that two-mode optical squeezing, as produced from a non-degenerate optical parametric oscillator (OPO), can produce twin entangled atom laser beams propagating in different directions [2]. This may prove to be an easy way to generate entangled atoms to test the behaviour of spatially separated, entangled massive particles. By considering the full multimode dynamics of the optical field, we have further shown that entanglement can be generated between the transmitted light and the atom laser beam. 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.

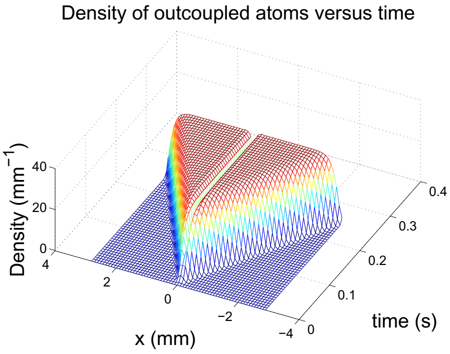

Figure 1: Density of outcoupled atoms for twin atom lasers produced from outcoupling atoms from a BEC using two-mode optical squeezing. [2]

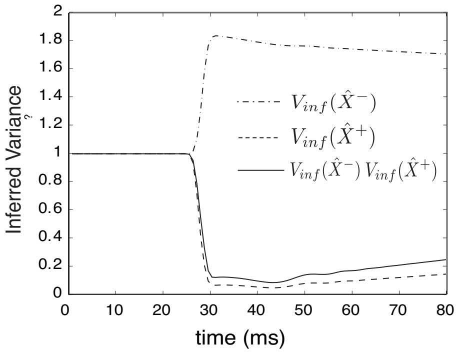

Figure 2: Entanglement between the atom laser and the transmitted optical beam. Amplitude and phase quadratures of the atom laser beam can both be inferred to well below the quantum limit by measuring the optical beam.

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A minimally destructive real time BEC detector

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In optical detection of BECs, every absorbed photon leads, at least, to the loss of an atom from the condensate. If the lifetime of the BEC is not to be reduced drastically by the detection process, this results in stringent limitations on the light power that can be absorbed by the condensate, leading to a fundamentally limited maximum achievable signal-to-noise ratio of the measurement [1]. Future experiments, such as applying feedback to stabilize an atom laser outcoupled from a BEC, require not only a nondestructive detection technique but also a readout of the data in real time. The detection bandwidth has to cover DC to MHz, the timescale on which BEC dynamics occur.

We have developed and characterized the first detector meeting all these demands while operating at the shot-noise limit [2]. This technology is complementary to current imaging techniques as our system does not supply spatial information, but rather temporal information about the peak density of a sample.

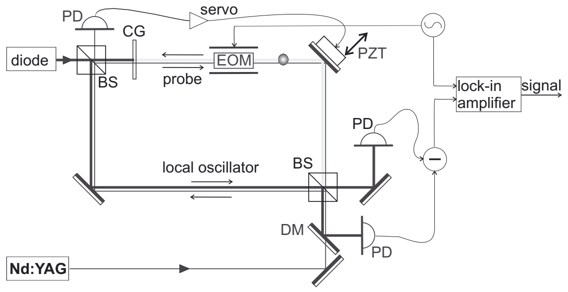

Fig. 1: Schematics of the detection system. BS: Beamsplitter, PD: Photodetector, CG: Color glass, DM: Dichroic mirror.

The detector is based on an unbalanced Mach-Zehnder interferometer (see Fig. 1) created with a diode laser operating close to the atomic resonance. A BEC (indicated by the circle) is meant to be placed in the picowatts carrying probe arm while the local oscillator of some milliwatts is passed around the atoms. The atomic column density is measured through the phase shift of the light due to the presence of atoms. Photodiodes are used as a detection device thus providing a bandwidth up to several megahertz with a real time readout of the data.

Modulating the frequency of the laser in the probe arm, we shift the signal into a frequency regime where the electronic noise of the photodetectors is low enough to allow for shot-noise sensitivity. For phase-noise suppression, the interferometer is locked using a second (Nd:YAG) laser that is far detuned with respect to the atomic resonance. We characterized the performance of the detector. Using these measurements, we calculate the sensitivity for a fractional change in the atom column density of a typical BEC (10^5 atoms confined to a volume of (10x10x50)$\mu\mathrm{m}^3$ with a lifetime of 1 s) to be $0.1\%/\sqrt{\mathrm{Hz}}$.

The detector is based on an unbalanced Mach-Zehnder interferometer (see Fig. 1) created with a diode laser operating close to the atomic resonance. A BEC (indicated by the circle) is meant to be placed in the picowatts carrying probe arm while the local oscillator of some milliwatts is passed around the atoms. The atomic column density is measured through the phase shift of the light due to the presence of atoms. Photodiodes are used as a detection device thus providing a bandwidth up to several megahertz with a real time readout of the data. Modulating the frequency of the laser in the probe arm, we shift the signal into a frequency regime where the electronic noise of the photodetectors is low enough to allow for shot-noise sensitivity. For phase-noise suppression, the interferometer is locked using a second (Nd:YAG) laser that is far detuned with respect to the atomic resonance.

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Piezo-locking a Diode Laser with Saturated Absorption Spectroscopy

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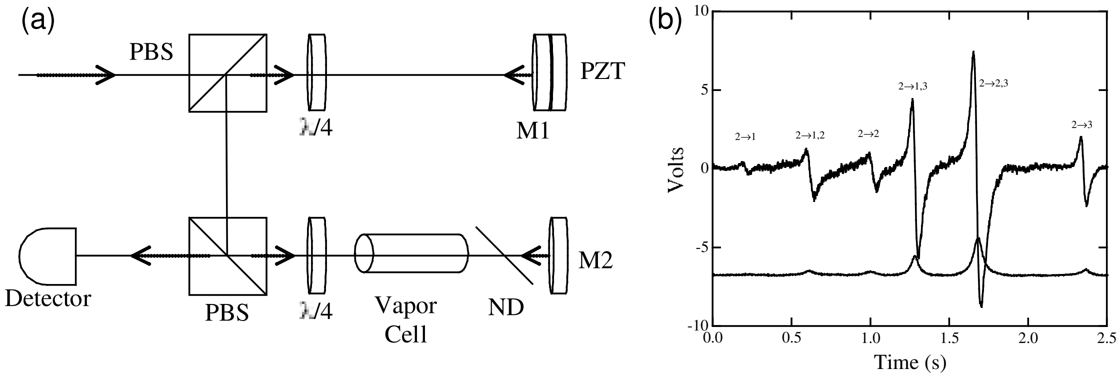
Saturated absorption spectroscopy is a ubiquitous method of frequency stabilizing diode lasers in many areas of atomic physics such as: spectroscopy, atomic clocks, laser cooling and Bose-Einstein condensation. Several methods for obtaining an error signal from an atomic transition are currently in use [1, 2]. Many research laboratories rely on commercial modulators to generate error signals . Although effective, the cost of a commercial modulator and its driving electronics (∼$4,000) is a very significant component of the total cost of a locking circuit. In the method described in this note, frequency modulation is provided by a mirror mounted on a piezo-electric transducer (PZT). Although this technique is used in quantum optics labs around the world to lock interferometers, to our knowledge it has not been applied to atoms. The PZT and its drive electronics replace the commercial modulator at one tenth the price. The setup is easier to use and, in our lab, provides superior performance for low bandwidth locking applications. For frequency stabilizing a laser to an atomic transition, we have used the configuration shown in Figure 1(a). A small portion of laser light is split off from the main beam going to our experiment. This is phase modulated by M1, which is attached to a PZT, and then sent to a standard saturated absorption spectrometer. The modulated saturated absorption signal is converted to an error signal using a commercial lock-in amplifier.



(a) Schematic diagram of one set up used for creating modulated light for saturated absorption spectroscopy and (b) Saturated absorption of the $5^2S_{\frac{1}{2}}F = 2 \rightarrow 5^2P_{\frac{3}{2}}$ transition for ^{87}Rb (lower trace) and the corresponding error signal (upper trace).

We have found that when the PZT is driven with a 5 V sine wave, there is sufficient modulation to create a strong error signal from the saturated absorption system. Typical error signals are shown in figure 1(b). With such a small driving voltage the error signal was substantial only at the resonant frequency. Two identically mounted PZT mirrors were tested, both having sharp resonances (Q 100) near 30 kHz. If higher modulation frequencies are needed, it may be possible to drive the PZT sufficiently hard at an overtone of the 30 kHz resonance. To demonstrate the stability of this setup, we have locked two external cavity diode lasers to different ^{87}Rb hyperfine transitions and determined the relative laser line-width by a beat measurement The optical beat measurement yields a peak with a full width at half maximum (FWHM) of 1.9 MHz, which is a convolution of the line-widths of the two lasers. Assuming the lasers have identical line-widths, the FWHM of each laser is 1.3 MHz. The lasers remain locked for many hours, allowing us to employ this method in all locking circuits used to produce, manipulate and probe Bose Einstein condensates in our lab.

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Quantum simulations of thermal Bose-Einstein condensates.

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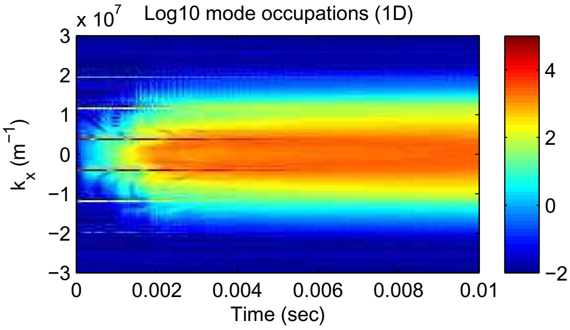
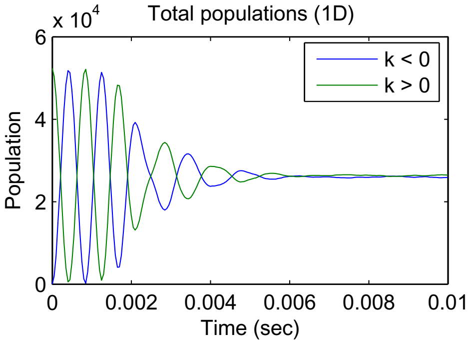
This project makes use of the truncated Wigner method for solving the quantum evolution of a Bose-condensed gas [1]. The inclusion of initial quantum noise means the technique can represent quantum corrections to the classical field equations of motion, and so can treat a different set of problems to the classical field method. The validity of the approximation relies on simulations either being for short times, or for more particles than modes. This project involves collaborations with the University of Otago, as well as both theory groups within ACQAO at the ANU, and relates the atom-laser project at ANU, as well as the He* and atom-chip BEC projects.

The truncated Wigner method has been applied to the problem of the "Bosenova" [2]. In these experiments the scattering length was of 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 have postulated that this may be due to quantum effects that are included in the Wigner description. Work is continuing on applying the numerical schemes developed for the classical field method for the trapped Bose gas to this problem. The three body loss terms in the master equation lead to multiplicative noise in the equations of motion, and these must be integrated using a stochastically stable algorithm.

The technique has also been applied to the loading of BECs into the band edge in an optical lattice combined with a magnetic trapping potential. The effects of interactions cause a loss of coherence in the Rabi cycling between momentum states, and the rapid generation of a large thermal component. The results can be understood in terms of energy conservation, and are in good agreement with experiments performed at Otago University, and we plan a joint publication.





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.* [4]. The numerical solution of the GPE results in unphysical spikes in the density indicating instabilities. The addition of quantum noise seems to smooth these spikes and results in the generation of a thermal component, in line with the results of the previous project. In certain situations soliton trains are observed to form.

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Skyrmions in trapped BECs

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Experimental dilute gas BECs achieve the conditions of the classical field Gross-Pitaevskii approximation, allowing topologically interesting structures to be investigated with unprecedented flexibility. We have previously identified, and shown how to overcome, the specific instabilities of skyrmions in trapped two-species atomic BECs, and hence demonstrated numerically their energetic stability [1]. The separate conservation of the two atomic species can stabilize the skyrmion against shrinking to zero size, while drift of the skyrmion due to the trap-induced density gradient can be prevented by sufficiently fast rotation, or by a laser potential.

Since then we have numerically surveyed the experimental parameters for which skyrmions are stable [2]. We have found that the range of rotation speeds over which the skyrmions are stable is small. For example, for too high speeds an unwanted vortex enters the outer skyrmion component, see right figure below. This sensitivity to parameters may be a difficulty for experiments. A particular goal was to reduce the number of atoms required for stability against skrinkage to below the nine million used in reference [1]. In a spherical trap we could only reduce this number by a factor of two or so, at the expense of even smaller stable parameter ranges.

The conclusion of our investigations is that it will be challenging to create stable skyrmions in an experiment due to their sensitivity to a range of parameters.

However we discovered a link betwen the superfluid velocity and the stability. The BEC component with the ring vortex, the outer component in the figure, is circulating around the ring singularity and back through the central core threading the line singularity of the other component. Since the volume of the central core is small the speed is high. The skyrmion becomes unstable as this speed becomes comparable to the speed of sound. This led to the idea that confining the ring vortex component with an optical vortex, rather than a BEC line vortex, might allow supersonic flows through the central core. This seems to be the case and is currently under investigation [3].

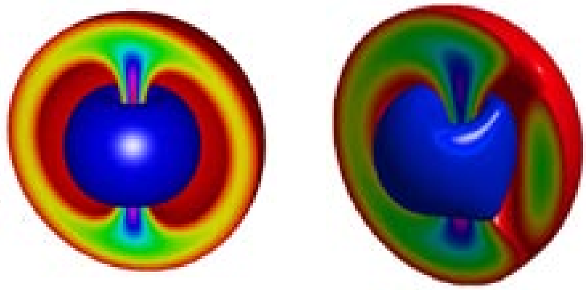

Figure: (Left) 3D density profile of a trapped skyrmion. The central torus is an isosurface of the atomic state forming a line vortex. The other atomic state forms a ring vortex: isosurfaces are shown for $x < 0$. On the $y - z$ plane between the isosurface sections, density is indicated by a colormap. (Right) An additional line vortex enters the outer component due to fast rotation.

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Quantum-Imaging: detecting spatial multimode quantum information

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Laser beams are widely used to send and process quantum information. In our experiments we employ CW beams and squeezed light as the medium to carry modulation which is defined better than the conventional quantum noise or shot noise limit. Normally all the information is contained in one mode. However, it is possible to surpass this limit by using spatial information and thereby linking several optical modes. In our work we demonstrate simple techniques for encoding information in higher oder modes, through the modulation of the displacement and tilt of a beam.

Each spatial detector has a special set of eigenmodes, and it is these specific spatial modes of squeezed light that have to be generated. For example the eigenmodes of the simplest detector, the split detector, are the so called flipped modes with a π phase discontinuity across the beam. This was analyzed by in detail by the group in Paris and we demonstrated the improvements in accuracy in experiments at ANU in 2003. [1][2]

During 2004 we searched for the optimum detection scheme and found that for small displacements all the information about displacement and tilt of a conventional TEM_{00} beam is in the real and imaginary part of the higher order TEM_{01} and TEM_{10} modes. We also found that spatial homodyne detector, that is a homodyne detector with TEM_{01} local oscillator, is ideally suited for these measurements. That is that the eigenmodes are the Hermite Gaussian TEM_{01} and TEM_{10} modes. We found that the Split detector is only 80 % as efficient as the homodyne detector. [3]

We now have the first experimental demonstration that displacement measurements with spatial homodyne detectors are efficient and that we can measure displacements below the quantum noise limit, using squeezed light. Our next aim is to find more efficient ways of generating squeezed light in the TEM_{10} mode to demonstrate spatial entanglement and to look for practical applications of these new methods. In particular we have joined a European wide team which proposes, as part of the EU six framework, to investigate enhanced techniques for optical data storage.

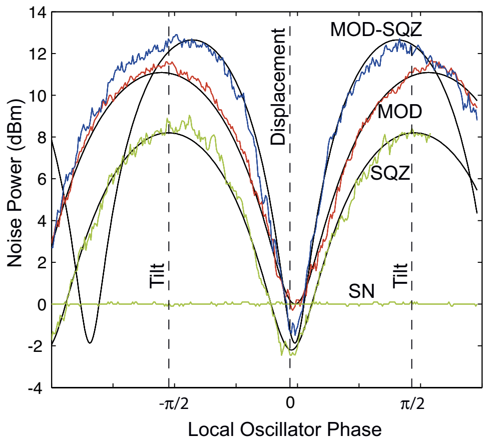

Figure 1: Spatial homodyne measurement with and without squeezing. The local oscillator has a TEM_{01} mode. The phase of the local oscillator is scanned, the measurement cycles from displacement (minimum) to tilt measurement (maximum). The classical measurement, without squeezing, are given by the quantum noise trace (MOD), the displacement d_{CL} and tilt t_{CL}. The measurements with squeezing, trace (MOD-SQZ) for the quantum noise, d_{SQZ} and t_{SQZ}, show the improvement. We can measure a displacement below the shot noise, trace (SN)

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Generation of spatial multi-mode squeezed light

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Laser beams are widely used to send and process quantum information. Normally all the information is contained in one mode. However, multiple orthogonal spatial modes can carry complex quantum information and at the same time are the optimum basis for measurements of the position and momentum of the beam [1]. In our work we demonstrate simple techniques for encoding information in higher oder modes, through the modulation of the displacement and tilt of a beam [2]. Squeezed light in these higher order modes are the resource for future multimode quantum communication applications [3].

We have developed and demonstrate for the first time techniques for the direct generation of squeezed light in the TEM_{10} and TEM_{20} modes, using an optical parametric amplifier pumped at 532, and seed phase sensitively amplifying at 1064 nm. Here all experimental parameters, such as pump beam geometry, the mode dependent phase matching temperature and cavity length and have been optimized for the generation of squeezed light. The results, Fig. 1, confirm the predictions based on the calculated mode overlap between the pump and the amplified mode and the phase selective mode matching conditions.

The threshold of the OPA increase for the higher modes and the degree of squeezing is consistent with the predicted performance. The way is now open to use this multi mode squeezed beams for quantum information applications.

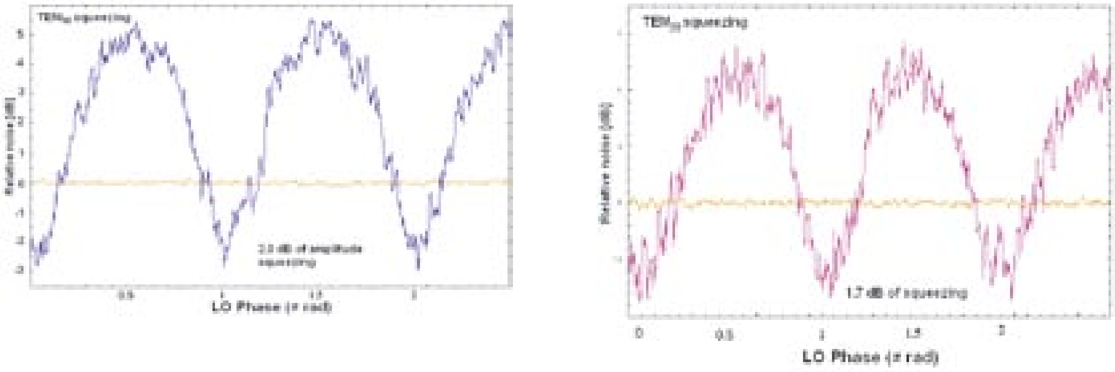

Figure 1: Example of the squeezing traces for TEM_{10} with 2.9 dB of noise suppression below the quantum noise and TEM_{20} with a noise suppression of 1.7 dB

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Ultra-cold Fermi gases

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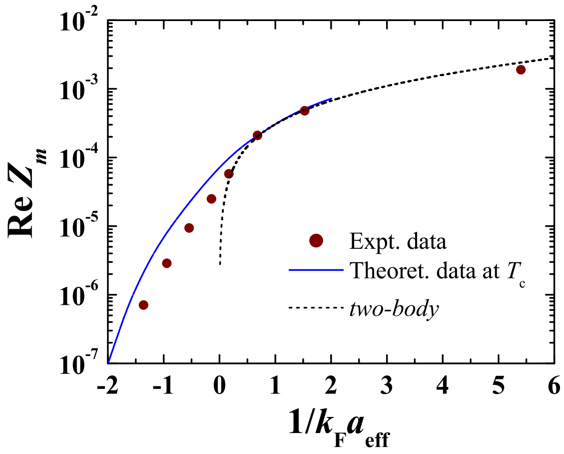
Molecule formation in ultracold degenerate quantum gases is one of the central topics in the overall ACQAO program, due to the strong quantum correlations in these systems. An experimental program in ultra-cold molecule formation using fermionic ^{6}Li near a Feshbach resonance is underway at the SUT node of ACQAO. The work described here provides theoretical support for possible experimental investigations of superfluidity near the Feshbach resonance. There are additional links being established internationally with experimental groups at Ecole Normale Superieure (France), and Innsbruck University (Austria), which have already verified some earlier predictions.

In these systems, the inter-atomic interaction strength can be varied by tuning the energy of a near-resonant molecular state with a magnetic field. These rapid experimental developments constitute an ideal testing ground for theoretical studies of the BCS-BEC crossover. However, theoretical results available in the literature are limited in the strongly correlated unitary regime. In 2005, we developed the theory of the BCS-BEC crossover both above and below the transition temperature. In this work we have used diagrammatic perturbation theory methods to treat an interacting ultra-cold Fermi gas with a Feshbach resonance [1]. The strong fluctuations of the preformed Cooper-pairs and of the Feshbach molecules have been incorporated within a self-consistent T-matrix approximation above threshold, while inter-molecular interactions were successfully included below threshold.



We have applied this theory to explore the normal phase of the gas at BCS-BEC crossover, including resonance width effects. It was found that the superfluid transition temperature increases monotonically at all widths as the effective interaction between atoms becomes more attractive. Furthermore, we have characterized the fraction Z_m (see figure) and lifetime of Feshbach molecules at T_c. As shown in the figure, our many-body calculations agree much better than simple two-body theory with the recent measurements on a gas of ^{6}Li atoms near the broad Feshbach resonance at 834 Gauss [2].

Next, we have calculated a theory for a superfluid Fermi gas near the BCS-BEC crossover [4], with the inclusion of pairing fluctuation contributions to the free energy. We obtained an equation of state of the gas, and compared it with recent four-body scattering calculations and Quantum Monte Carlo simulations at zero temperature. Excellent agreement is found for all interaction strengths. The temperature dependence of the equation of state was also studied in the unitary limit, and agrees with available path integral Monte Carlo results. Furthermore, by using the local density approximation we have studied the superfluid Fermi gas in a harmonic trap, showing that in experiments the temperature can be usefully calibrated by making use of the entropy, which is invariant during an adiabatic conversion into the weakly-interacting limit of molecular BEC [5].

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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 in both ANU and the University of Otago.

The technique being utilised 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]. An essential part of the method is that there is a well-defined mode cutoff, so that non-classical modes are eliminated from the numerics. This is in the same spirit as laser theory, where the highly occupied modes of the electromagnetic field can be treated classically.

The application of the classical field method to harmonically trapped Bose gases was eventually published in 2005 [2]. 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.* [6]. 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 of Ref. [6]. This work has been accepted by Physical Review Letters.

Also in 2005 a detailed calculation of measuring temperatures for classical fields has been published [4], and a further work detailing the boundaries of the classical region has been submitted [5]. The code base for the classical field method in a harmonic trap has also been revamped in an effort to make it easier to modify for particular situations.

The classical field method has also been applied to the 2D homogeneous Bose gas, where the Kosterlitz-Thouless transition occurs rather than BEC. We have successfully identified regimes of vortex pair breaking and its relationship to the superfluid fraction of the system, as well as observing more complex vortex structures. Current work is obtaining a phase diagram for a fixed number of particles. We are also investigating using the scissors excitation mode as a signature of superfluidity for the Kosterlitz-Thouless phase in a trapped gas.

Related work has been performed on the formation of a vortex lattice, and in particular investigating the calculations reported in Lobo *et al.* [8]. We have identified numerical errors in these calculations, and are currently repeating them with a view to commenting on their physical implications.

Finally, the numerical work on the kinetic theory of the continuous-wave atom laser has been completed. This should be submitted for publication in the coming months.

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Quantum atom optics with fermions from molecular dissociation

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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. This can be regarded as a new development into quantum atom optics with *fermions*.

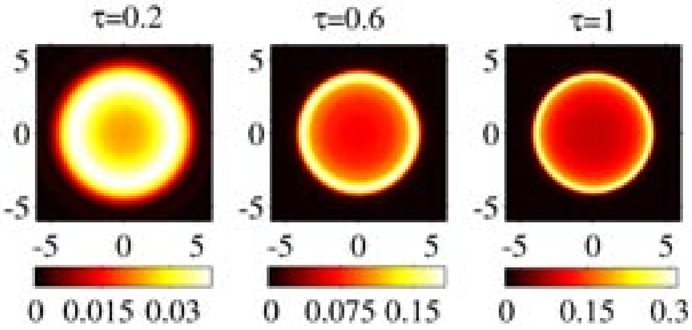
The rapid advances in the experimental control of ultracold quantum gases have now reached the stage where atomic correlations can be directly accessed via the measurement of atom shot noise. Recent breakthrough experiments demonstrating this include quantum correlation measurements on atoms created through dissociation of weakly-bound molecules near a Feshbach resonance [1] and with atoms in a Mott insulator phase released from an optical lattice [2].

Given the close parallels with quantum optics, and the fact that its most celebrated applications have been achieved using entangled photon pairs from parametric down-conversion, we are motivated to study a matter-wave or atom optics analog of this resource.

In this project summary, we report [3] on our studies of the *fermionic* counterpart of the optical parametric down-conversion. This can be achieved through dissociation of molecules consisting of fermionic atom pairs in two different spin states, as demonstrated in recent experiments at JILA (Colorado, USA) using rf photo-dissociation of $^{40}K_2$ dimers [1]. The same experimental techniques can be applied to the planned experiments at the SUT using lithium. Our work expands the paradigm of quantum atom optics with fermions and points out at conceptual differences in the notions of shot-noise and maximally correlated states for fermions versus bosons.

An important issue both in these experiments is the use of optical imaging techniques to detect atoms. As these typically only resolve the density in two dimensions, one must calculate the *column density* correlations. These include an average over the third dimension in the propagation direction of the laser used to detect the correlated atoms.

Within a simple analytically solvable model describing this system, we study the dynamics of dissociation and analyze the resulting atomic pair correlations. For short time scales, the results provide a qualitative theoretical account of the experimental measurements at JILA [1].



The above figure shows snapshots of the momentum column density for dissociated atoms at different times τ calculated using a simple, spatially uniform model. The last two frames show a clear ring structure around the central background and are consistent with the observed [1] absorption images of spatial column densities after expansion.

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Correlations between bosonic atoms dissociated from a Bose-Einstein condensate of molecular dimers

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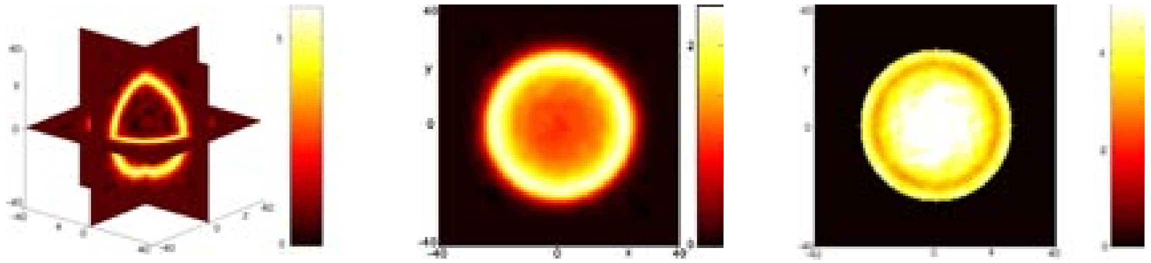
Dissociation of a molecular dimer produces two quantum mechanically entangled atoms with equal and opposite momenta in the molecule's rest frame. These atoms have Einstein-Podolsky-Rosen type correlations, and hence are of fundamental interest. It is possible to produce Bose-Einstein condensates (BECs) of molecules, and then to dissociate them as in Ref. [1], so that these correlations may be explored experimentally [2] in the regime of large number of particles.

In this project [3] we use quantum field simulations to investigate the conditions under which the atomic correlations may be observed. We use stochastic methods based on the the positive-P representation. This allows us to extend the analytical results which are known for the case of a spatially uniform system and undepleted, classical molecular field [4]. Important limitations on our method are that it is restricted to bosonic atoms, and that the positive-P simulations eventually fail as the simulation time increases, particularly when two-body scattering is included.

Since our simulations are three-dimensional (3D) we can both investigate the full spatial structure of the atoms and their correlations, and simulate experimental measurement methods, including time-of-flight expansion in free space and absorption imaging. In particular, we integrate along the propagation direction (z) of the imaging laser and obtain atomic (2D) column densities. We find that these images may then be correlated to reveal non-local density-density correlations, which we quantify via

$$g_z^{(2)}(\mathbf{r},\mathbf{r}') = \frac{\langle :\hat{n}_z(\mathbf{r})\hat{n}_z(\mathbf{r}'):\rangle}{\langle \hat{n}_z(\mathbf{r})\rangle\langle \hat{n}_z(\mathbf{r}')\rangle},$$

where $\hat{n}_z(\mathbf{r}) = \int dz \hat{\Psi}^\dagger(\mathbf{x})\hat{\Psi}(\mathbf{x})$ is the column density operator, and $\hat{\Psi}(\mathbf{x})$ is the atomic field operator [$\mathbf{x} = (x, y, z)$, $\mathbf{r} = (x, y)$]. We analyse these correlations as a function of the size and geometry of the initial molecular condensate, with examples shown in the figures.



Figures. **(Left)** Slice plot of atomic 3D density after dissociation and time-of-flight expansion, starting from a spherical molecular BEC. Values in all plots are indicated by a color scale. The density is in units of $10^{-5}n_0$, where n_0 is the peak density of the initial molecular condensate. **(Centre)** Atomic column density $\langle \hat{n}_z(\mathbf{r})\rangle$ as a function of $\mathbf{r}$; the scale is in units of $(10^{-3}n_0)$m, i.e. in inverse area units. **(Right)** Second-order correlation function for column densities after expansion at diametrically opposite locations, $g_z^{(2)}(\mathbf{r},-\mathbf{r})$. This particular correlation is the strongest among all other non-local correlations, reflecting the intrinsic momentum correlations of dissociated atoms before expansion.

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Towards a Molecular Bose-Einstein Condensate

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The objective of this project is to produce a molecular Bose Einstein condensate (MBEC) via the association of ultracold fermionic ^{6}Li atoms. 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 [1], and to investigate the coherent interaction between the MBEC and a quantum degenerate atomic gas and dynamical processes such as Bose enhanced molecule formation.

Historically, most of the activity in cold atom research has involved bosonic atoms. There is also a wealth of interesting physics to be found in cold fermionic systems. In particular, for our work, investigations in recent years by several groups [2, 3, 4] have demonstrated that it is possible to produce a very stable molecular BEC composed of fermionic ^{6}Li atoms, which exhibit lifetimes of some tens of seconds, compared with typically 100 μs in the case of quantum degenerate molecular gases that have been obtained from bosonic ^{23}Na, ^{87}Rb or ^{133}Cs 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.

In our experiment a σ^- Zeeman slower is used to produce a continuous beam of isotopically-enriched ^{6}Li atoms at speeds low enough to load a magneto-optical trap (MOT). We currently have a flux of slowed atoms of 2 x 10^7 atoms/s loading the MOT with about 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 about 30 s. The near-resonant slowing/trapping/cooling light, at 671 nm, is produced by injection-locking several free running laser diodes to a Toptica DL100 extended-cavity master laser, with the various frequency offsets produced using acousto-optic modulators.

The next experimental step is to transfer the atoms from the MOT to a far-off-resonant optical dipole trap (FORT), which is used to trap and evaporatively cool the atoms and molecules. The FORT consists of a focussed beam from a 20 W single-frequency Yb:YAG laser at 1030 nm. The scattering length of the atoms will be controlled magnetically via a Feshbach resonances at about 834 Gauss. Initial evaporation in the optical dipole trap is performed at magnetic field strengths that enhance three-body recombination to form ^{6}Li$_2$ dimers, similar to the scheme used in [2].

Theoretical research on molecular BECs generated from cold atomic gases is being carried out. 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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Quantum noise properties of matter-wave gap solitons

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The active research into quantum properties of nonlinear many-particle systems has enabled control and engineering of quantum noise in nonlinear optics [1]. Quantum noise reduction of optical signals below the shot-noise level (uncertainty squeezing), and quantum entanglement of interacting optical pulses are at the core of the applications of non-classical light in quantum interferometry, precision measurement, and quantum information processing. Non-spreading optical *solitons*, supported by dispersive nonlinear media, proved to be the best candidates for experiments on quantum noise reduction and entanglement due to their robust dynamics and scattering properties [1]. It has been recognized [2] that general methods of quantum optics could apply to weakly interacting ultracold atoms in a Bose-Einstein condensate (BEC). Production of quantum correlations in the macroscopic quantum states relies on interactions between the atoms, the mechanism that is analogous to optical Kerr effect.

Recently, *gap solitons* in a *repulsive* BEC, supported by periodic potentials of optical lattices, have attracted a great deal of attention due to their controllable interaction and robust evolution uninhibited by collapse [3]. This project is dedicated to studies of quantum noise squeezing and quantum correlations of gap solitons in a Bose-Einstein condensate loaded into a one-dimensional optical lattice. By employing a linearized quantum theory we found that quantum noise squeezing of gap solitons, produced during their evolution, is enhanced compared with the atomic solitons in a lattice-free case (see Fig. 1) due to intra-soliton structure of quantum correlations induced by the Bragg scattering in the periodic potential [4]. We also demonstrated that nonlinear interaction of gap solitons in dynamically stable bound states can produce strong atom-number correlation between the soliton pairs [4].

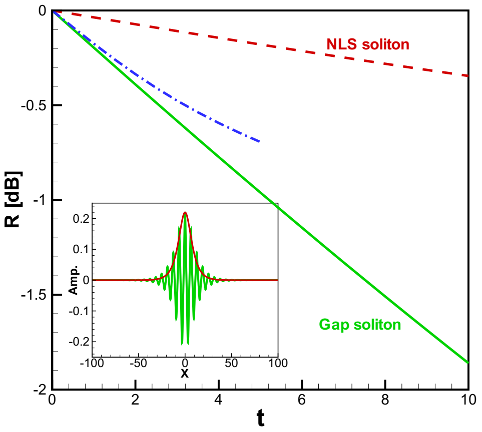

Fig. 1 Evolution of the optimal squeezing ratio for the gap soliton (solid), its near-band-edge envelope approximation (dot-dashed), and the lattice-free soliton (dashed), demonstrating the enhancement of squeezing in a lattice. Inset: spatial profiles of the gap soliton and its envelope.

We also demonstrated that nonlinear interaction of gap solitons in dynamically stable bound states can produce strong atom-number correlation between the soliton pairs [4]. The nonlinear interaction between solitons in a pair could therefore induce entanglement and hence nonseparability of the bound state. This entanglement can potentially be exploited in BEC atom number detection by implementing analogs of quantum nondemolition measurements based on entangled pairs of optical solitons [5]. Potential advantage of gap solitons compared to the lattice-free atomic solitons is the long-lived nature of the bound states which are pinned by the lattice and do not break-up as a result of evolution.

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Matter-wave gap vortices in three-dimensional optical lattices

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Weakly interacting Bose-Einstein condensates (BECs) in optical lattices acquire a band-gap structure of Bloch-wave spectrum, which modifies the dispersion properties of BEC wavepackets and enables nonlinear localization of a condensate in the spectral gaps. In higher-dimensional periodic potentials both the symmetry and dimensionality of the lattice play an important role in the formation of the nonlinearly localized states of the condensate. Within the framework of a continuous mean-field model we have shown that, in two- and three- dimensional optical lattices, the nonlinear localization of BEC with repulsive atomic interactions is possible within a complete (finite) gap of the Bloch-wave spectrum. The localized states take the form of bright atomic solitons or *vortices* [1, 2].

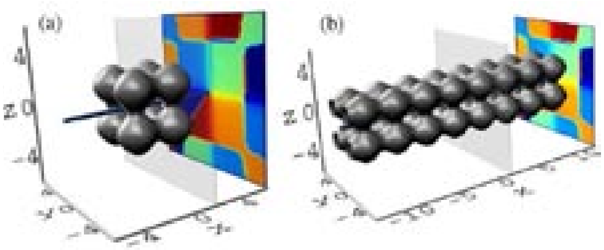
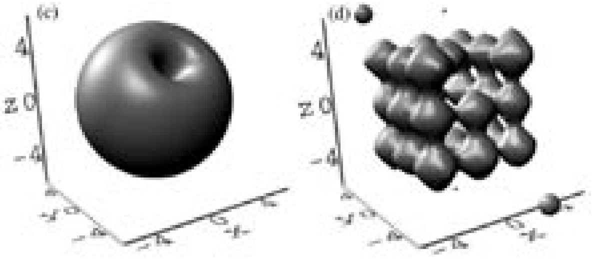


Figure 1: Condensate wavefunction $\psi(x, y)$ of the (a) fully spatially localized and (b) extended matter-wave gap vortices ("vortex stacks")in a 3D optical lattice. The phase map demonstrates the $0 \rightarrow 2\pi$ ramp at an arbitrary cross-section of the vortex. Solid lines indicate directions of vortex lines.



Simulation of the non-adiabatic excitation of a gap vortex. Shown are (c) initial state - a vortex line in a spherically symmetric BEC cloud, and (d) the result of the evolution of the condensate suddenly released into a 3D optical lattice. The final state is a broad spatially localized gap vortex.

Vortices can be supported by the 3D lattice despite the absence of rotational or translational symmetries [2]. They are characterized by a nonzero vortex-like density flow around the core and an atomic density profile which is strongly modulated by the lattice [Fig. 1 (a,b)]. The core of a gap vortex preserves the characteristic phase structure of a conventional vortex, whereas its tails are characterized by a nontrivial phase pattern associated with the underlying Bloch state. A 3D lattice can support fully spatially localized gap vortices [Fig. 1(a)], as well as extended vortex lines [Fig. 1(b)]. The remarkable feature of spatially extended vortex lines in a lattice is their stability against transverse perturbations.

Finally, we have demonstrated that a *non-adiabatic* loading of the 3D condensate with a single vortex prepared in a magnetic trap into a 3D optical lattice can lead to localization of broad high-density vortex states [Fig. 1(c,d)]. The spatial structure of these states links them to the recently observed self-trapped nonlinear states in 1D optical lattices [3], and makes them likely candidates for experimental observation.

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Information delay via electromagnetically induced transparency

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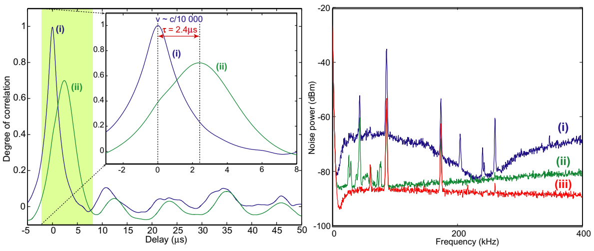
Quantum memory is an essential component for quantum computation. Electromagnetically induced transparency (EIT) [1] has been proposed as a possible scheme for achieving quantum memory via the manipulation of dark-state polaritons [2]. Experiments on the slowing of optical pulses through an atomic medium via EIT have been reported [3]. There have also been many experiments studying the storage of optical pulses in atomic vapour cells as well as in laser-cooled and trapped atoms [4]. However, recently there have been alternative interpretations on the storage of information via EIT [5].

Our aim is to study the possibility of using EIT to store quantum information. We approach this problem by considering the slowing of information in the form of modulation sidebands on an optical beam. We demonstrate a quantum noise limited delay ($\sim c/10000$) of the conjugate pair of amplitude and phase quadratures of a continuous wave optical beam via EIT in a Rubidium vapour cell. Cross-quadrature coupling between the amplitude and phase quadratures have also been studied and was shown to be insignificant.



Left figure: Delay of a 200 kHz band of modulated amplitude or phase signals via EIT. (i) Auto-correlation of the input signal. (ii) Correlation between the input and output signals after EIT. The observed information delay is 2.4 μs which corresponds to a group velocity reduction to $v \sim c/10000$. Curve (ii) is slightly broader than curve (i), indicating a frequency dependent delay for various sideband frequencies. The periodic feature shows the presence of a laser locking modulation in the laser spectrum. Right figure: Phase quadrature spectral results for the photocurrent subtraction between the output probe beam after EIT and the input probe beam with a cable delay (equal to that of the EIT delay). The input probe beam was modulated with broadband noise. (i) Subtraction with EIT present and gain G_1 for the delayed input probe beam signal. (ii) Subtraction without EIT. The loss due to EIT was simulated optically using a variable beam-splitter. The gain G_1 for the delayed input probe beam signal was maintained but the cable delay removed. (iii) Quantum noise limit for the system, taking into account gain G_1. Similar results for the amplitude quadrature were obtained.

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Modeling of EIT-based Quantum memories using phase-space methods

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One of the milestones towards the realization of quantum computation is a device that allows the coherent storage of quantum information. The Heisenberg Uncertainty Principle sets a limit on the quality of stored quantum information that depends on direct measurement and subsequent reconstruction [1]. Experimental and theoretical research are therefore directed towards using Electromagnetically Induced Transparency (EIT) as a mechanism to facilitate quantum information storage in a manner that allows the circumvention of the HUP limit [3]. Two optical fields, a weak probe and a strong control beam, driving two transitions of a Lambda structure will set up quantum interference that leads to a extremely narrow transparency window. The associated steep dispersion profile will result in significant slowing of the group velocity of the probe light. By adiabatically switching off the control field, information encoded in the probe field can be mapped onto the coherent superposition of the two atomic ground states, thus allowing storage of quantum information. This information can then be retrieved at a later time by the switching on of the control field. By encoding amplitude and phase modulations onto the sideband of a propagation light pulse, and taking into account atomic noise and decoherence of a realistic experiment, we construct a model to quantify the efficacy of quantum information storage via EIT.

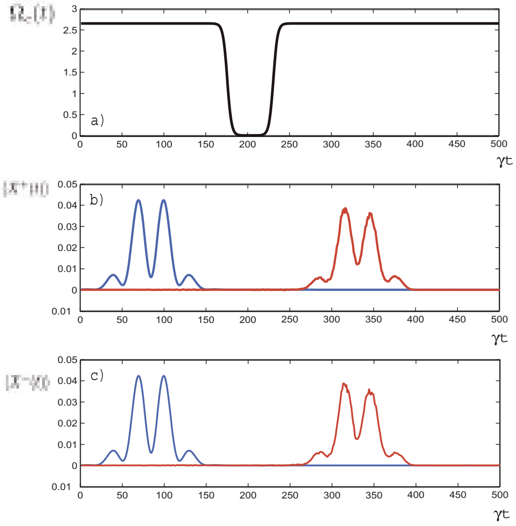

Figure 1: Storage of Amplitude (b) and phase (c) quadratures of a light pulse when adiabatically switching off and on the coupling beam (a)

Our recent work has shown that theoretically both quadratures can be delayed with no added noise. These calculations were made by solving the Maxwell-Bloch equations with Langevin terms in a weak probe approximation regime [2]. We are now using an analytical as well as a numerical model to calculate the degradation of the signal to noise ratio when the coupling beam is switched off and on. Our analysis takes into account the adiabatic switching process of the control beam without making a weak probe approximation. A set of stochastic differential equations in the positive-P representation is developed. The solution of these equations in time and space is obtained using the XMDS package. Initial results suggest that the memory produces no excess noise but has a non-negligible absorption due to the finite width of the transparency window [Fig. (1)].

We plan to use the quantum information benchmarks for quantifying storage protocols efficacies. Signal transfer coefficients, conditional variances [4] and average fidelities will be calculated to examine the advantages of the EIT process in an analogous way to quantum teleportation. These results will tell us the experimental parameters required to implement EIT-based memories in the quantum regime.

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UV Light from a PPKTP SHG for Generation of Squeezed Light at 795nm

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Squeezed Light is the basic resource for the generation of entangled light and hence for the realisation of protocols in quantum information processing and quantum communication. The generation, transmission, manipulation and detection of such non classical light states is well established. The storage of such states in atoms e.g. EIT, is currently receiving increasing interest (cf. report of M. Hsu). A tunable squeezed light source at atomic wavelengths, such as the ^{87}Rb D1 line (795nm), is required for quantum networking and successful demonstration of quantum memory with non classical light, but may also be of interest for interactions of non classical light with BECs and may lead to squeezed atom lasers [1]. Generation of squeezed light at 795nm is difficult and only recently has there been successful generation of 1dB of squeezed light via periodically poled (PP) wave guides [2]. In our approach, we use PPKTP inside a cavity for second harmonic generation (SHG) which will be coupled into an optical parametric amplifier (OPA) to generate squeezed light.

KTP is used due to low losses and high non linearity, and, as birefringent phase matching is impossible for KTP at this wavelength periodic poling is used. The setup for the SHG is shown in Figure 1. The KTP crystal is placed inside a bow tie cavity which is resonant for the infrared (IR) light, but allows the UV to escape after the crystal. Phase modulation sidebands are imposed on the pump beam to allow for Pound Drever Hall locking. The pump beam is mode matched to the cavity waist of 240μm and the waist created inside the crystal corresponds to 40μm. This waist size is a compromise between accessing the maximum non linearity and minimising thermal effects which makes the system difficult to stably operate due to absorption of the UV light [3].

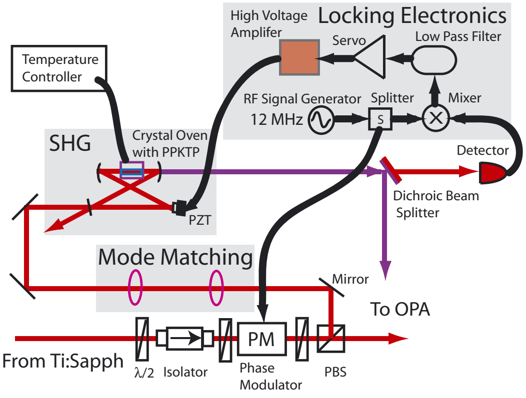

Figure 1: SHG experimental setup

Figure 2 shows the results of the output power and efficiency of the SHG as a function of the input power, for the locked and scanning operation of the cavity. For these measurements an input coupler of 88% was used, corresponding to a cold cavity finesse of 50. Up to 250mW UV light (corresponding to more than 40% efficiency) was produced at 600mW input power in the scanning operation. When the cavity was locked, this was reduced to ~ 180mW (30% efficiency). It should be noted that the efficiency has not been corrected to account for imperfect mode matching or losses in the UV. The disparity between the scanning and the locked operation is caused by locking difficulties due to heating of the system. However, at moderate input power levels (400-500mW) the SHG can be stably locked to yield 100-150mW of UV. With this amount of power we should be able to pump an OPA operated at approximately 50% of the threshold power to generate squeezed light at 795nm. By adjusting the phase matching temperature of the crystal, the operation wavelength of the SHG and ultimately of the OPA can be tuned by a few nanometers.

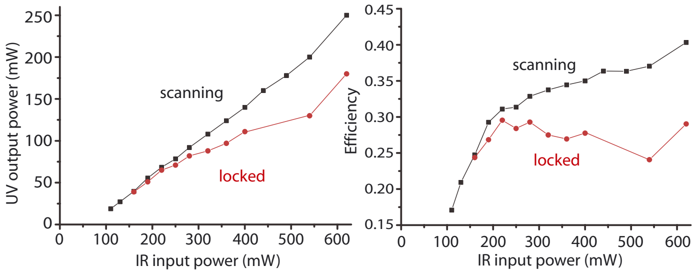

Figure 2: SHG output power and efficiency

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Simulations of polarization squeezing of ultrashort pulses in fibres

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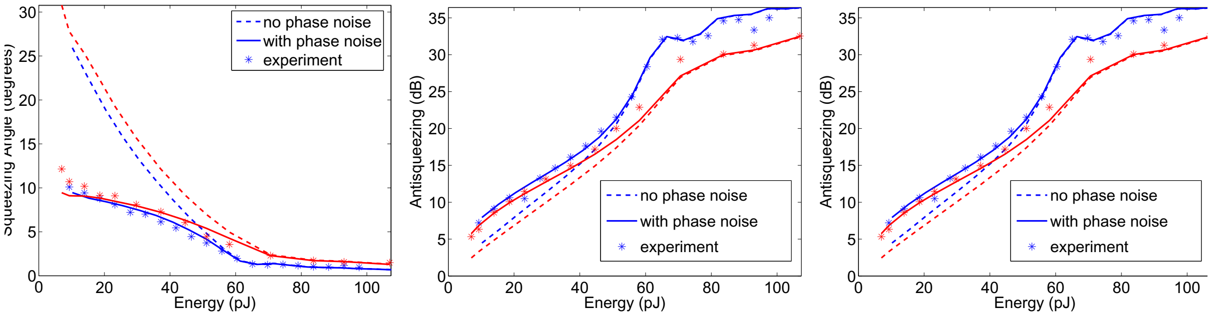
Polarisation squeezing in optical fibres can efficiently produce highly squeezed light[1]. Because the experiments operate in a very nonclassical regime, the results are very sensitive to additional nonlinear and thermal effects in the fibre. To quantitatively characterise such experiments, we perform 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. 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 identical pulses propagate along orthogonal polarisation axes of a polarisation-maintaining fibre. The emergent, squeezed pulses have same intensity, temporal overlap and $\frac{\pi}{2}$ phase shift (via a feedback loop). The pulses are combined on a half-wave plate and the squeezing 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 of a radiation field propagating along a fibre, including 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 $\alpha^R(\omega)$. In all, we have $> 10^8$ photons in $> 10^2$ modes, corresponding to an enormous Hilbert space.

To simulate such a system, we use a truncated Wigner technique[2], which provides an accurate simulation of the quantum dynamics for short propagation times and large photon number. Both these conditions are satisfied in the current experiments. The quantum effects enter via initial vacuum noise, which makes the technique ideally suited to squeezing calculations.



Phase-space rotation angle θ, antisqueezing and squeezing for $L_1 = 13.4\mathrm{m}$ (red) and $L_2 = 30\mathrm{m}$ (blue) fibres. Excess phase noise is determined by a single-parameter fit for each fibre length.
Parameters: $t_0 = 74\mathrm{fs}$, $z_0 = 0.52\mathrm{m}$, $\overline{n} = 2 \times 10^8$, $E_s = 54\mathrm{pJ}$, $\lambda_0 = 1.51\mu\mathrm{m}$

Typical results are shown in the figures, for 13.4m and 30.0 m fibres. The theoretical results for both squeezing and antisqueezing closely match the experimental data, after estimated linear losses of 24% are taken into account. As expected, the level of squeezing generally increases with input power. However Raman effects limit squeezing at very high intensity, and this effect is more pronounced in the longer fibre. The effects of excess phase noise, due to depolarising guided acoustic wave Brillouin scattering (GAWBS), is evident at low pulse energies where the Kerr effect is weaker.

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Quantum computation with diatomic qubits in optical lattices

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Recently, several quantum computation schemes utilizing ultracold dipolar molecules trapped in optical lattices were suggested [1]. The coupling due to dipole-dipole interactions between molecular bits is strong enough to induce entanglement and hence to realize a set of universal quantum logic gates. However, the electric dipole-dipole interaction between molecules can not be controllably switched off and on. This lack of control requires additional refocusing procedures to eliminate the effects of the non-nearest-neighboring couplings.

The other possibility to perform quantum computation using diatomic bits is provided by optically induced atom-molecular coherence. Raman transitions technique has already been successfully used to produce the ultracold heteronuclear molecules with large electric dipole moments [2]. We suggest a new scheme for quantum computation based upon diatomic qubits with conditional electric dipole-dipole interactions [3]. These are realised by two different species of Bose-condensed atoms trapped in a deep optical lattice. In a Mott insulator state with only two atoms (and only one atom of each species) per site, Raman pulses can coherently couple the free atomic state with a bound state corresponding to ground state of diatomic heteronuclear molecules. The well-distinguished two-state behavior of every lattice site allows us to use each diatomic system per site as a qubit. Here, the scattering state and the bound molecular state encode the qubit states $|0\rangle$ and $|1\rangle$, respectively. Due to the dipole-dipole interaction between dipolar molecular states, the two-bit phase gate can be naturally realized by free evolution. This conditional dipole-dipole interaction can be controllably turned on and off. Combining the two-bit phase-gate with the single-bit Raman transitions, one can successfully implement a set of universal gates. We can also show that the strength of dipole-dipole interactions guarantees the performance of a large number of quantum logic gates ($\sim 10^4$) per second [3].

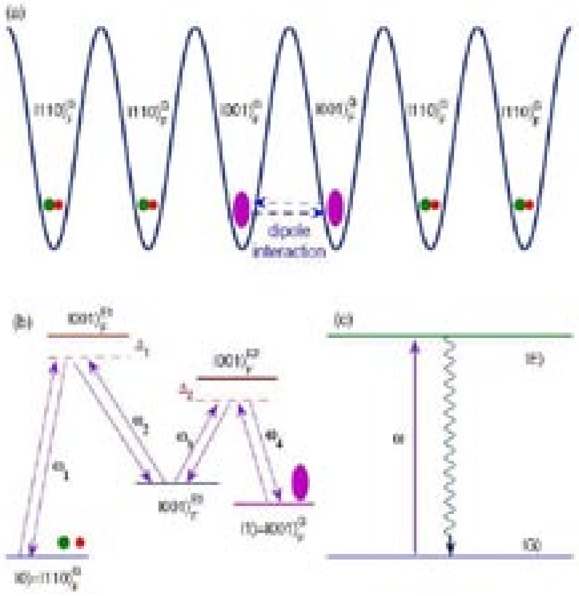

Figure 1: Scheme of quantum computation using diatomic qubits with conditional dipole-dipole interaction. (a) Diatomic qubits in one-dimensional optical lattices. The dipole-dipole interaction appears when neighboring bits occupy the molecular state. (b) Single-bit operation with optimally controlled processes (OCP) [4] sandwiched Raman transition. F denotes the Fock states, and G denotes the ground states. The first OCP transfers the ground molecular state to an excited one, the Raman pulse realizes the required superposition of the excited molecular state and the scattering state of atoms, and then the second OCP transfers the excited molecular state back to the ground one. (c) Read-out with photon scattering. The diatomic qubits are illuminated with a circularly polarized laser beam tuned to the cycling transition from the ground state $|G\rangle$ of the selected particle (atom A, atom B, or molecule C) to the corresponding excited state $|E\rangle$. If there are particles in $|G\rangle$, the photomultiplier will detect the scattered photons. Otherwise, there are no scattered photons.

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Superradiant phonon scattering from a hydrodynamic vortex

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We have shown that sound waves scattered from a hydrodynamic vortex may be amplified [1]. Such superradiant scattering follows from the physical analogy between spinning black holes and hydrodynamic vortices [2].

Sound waves are linear perturbations of the velocity potential ϕ. We considered a barotropic, inviscid, irrotational fluid, and assumed the unperturbed fluid flow was a vortex centred on the origin of our cylindrical coordinate system. We considered cylindrical wave solutions of the form $\phi(t, r, \theta, z) = \psi(t, r)e^{-im\theta}$, with angular wavenumber m. Assuming that the square of the speed of sound is proportional to the density, as is the case for a BEC, the density may be eliminated from the sound wave equation, which then becomes

$$\frac{\partial^2 \psi}{\partial t^2} - 2i\frac{m v_\theta}{r}\frac{\partial \psi}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left(rc^2\frac{\partial \psi}{\partial r}\right) + \frac{m^2}{r^2}\left(c^2 - v_\theta^2\right)\psi = 0\,. \tag{1}$$

where c is the unperturbed fluid's speed of sound, and v_θ is the polar component of the unperturbed fluid's flow speed. For irrotational flow, $v_\theta = \alpha/r$, for some constant α. In order to present analytical calculations we used the density profile

$$\rho(r) = \rho_\infty \frac{\left[(r - r_0)/\sigma\right]^2}{2 + \left[(r - r_0)/\sigma\right]^2}\,. \tag{2}$$

This is similar to the charge $l = 1$ vortex density profile for a BEC, but with the scale length given by the free parameter σ, rather than by the healing length χ. For single frequency waves of the form $\psi(t, r) = R(r)e^{i\omega t}$ we found that an incoming wave may scatter into an outgoing reflected wave and an ingoing transmitted wave. We found that superradiance occurs for $\omega < m\alpha/r_0^2$.

We are currently extending this analysis beyond the hydrodynamic approximation.

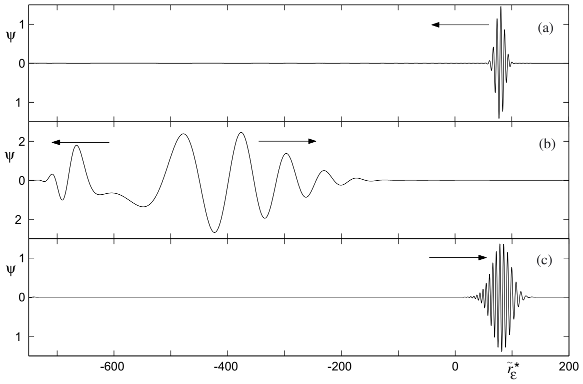

Figure. Wavepacket propagation from numerical solution of the wave equation. The real part of the wave packet is plotted versus the dimensionless modified radial tortoise coordinate $\tilde{r}^*_\epsilon$, defined in reference [1]. (a) the wavepacket is propagating towards the vortex. (b) the wavepacket has just split into reflected and transmitted parts. (c) the amplified reflected wavepacket.

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Representation theory

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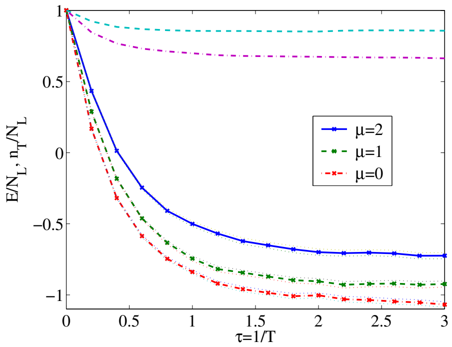
The physics of quantum, many-body systems underlies the whole ACQAO research program, and the methods outlined here are central to the analysis of quantum correlations in all of the ACQAO experiments. The development of tractable methods to simulate strongly correlated quantum systems of bosons and fermions 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 generalised and extended through stochastic gauges. The gauge techniques are able to deal with extremely complex irreversible master equations as well as unitary dynamics. Our simulation of time-reversible quantum dynamical behaviour in an interacting 10^{23} particle system [1] involved the largest number of interacting quantum particles ever simulated from first principles and received a favorable commentary [2] in **Nature's** *Research Highlights*.

Another, more radical generalisation can be obtained through the use of new operator bases, which determine the basic structure of the method and its suitability to different physical situations. By means of a Gaussian representation, we have developed phase-space techniques for *fermionic* systems[3].



Application to the well-known Hubbard model has allowed simulation to very low temperatures without the usual sign problem[4, 5]. The figure shows energy E per site versus inverse temperature τ for a 2D Hubbard model with 16×16 sites with chemical potentials $\mu = 2$ (solid), $\mu = 1$ (dashed) and $\mu = 0$ (dot-dashed). Curves without crosses give the number of particles per site for $\mu = 1$ (dashed) and $\mu = 0$ (dot-dashed). $U/t = 4$ and 100 paths initially. Dotted curves give an approximate sampling error.

Rapid advances in cold quantum gas experiments raise the possibility that quantum matter-wave properties of atoms may play a role in certain quantum-optical processes. When atoms are greater than one de Broglie wavelength from each other their fermionic or bosonic nature is unimportant. This condition holds for dilute high-temperature atomic samples, but not for degenerate quantum gases which are now readily available in laboratories around the world. It is thus necessary to develop methods which allow for a full quantum treatment of both the atomic and electromagnetic fields. In collaboration with L. I. Plimak at the University of Ulm and S. Rebic at the University of Camerino, we have applied phase-space techniques for the modelling of spontaneous emission in two-level bosonic atoms [6], using the positive-P and Wigner representations. Using a simple model we find that the dynamics of spontaneous emission can depend sensitively on the quantum statistics of the initial states and on the quantum coherences between the initial and final states of the atomic fields.

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Macroscopic entanglement and the Einstein-Podolsky-Rosen Paradox

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The aim of this project is to provide a strategy for detecting mesoscopic or macroscopic quantum superpositions in mixed states that better represent the output of physical systems that can be used to generate entanglement. 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.

Crucial to the field of quantum information is the concept of quantum entanglement. Einstein, Podolsky and Rosen [1] first pointed to the paradoxes of spatially separated quantum entangled state in their now famous EPR argument of 1935. Schrödinger in his essay [2] that same year made particular mention of the paradox of macroscopic entanglement, 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.

Experiments [3, 4] 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 [5] and a review incorporating experimental achievement is being written by invitation, to be submitted to Reviews of Modern Physics. The criteria have recently been applied [6] to give predictions of measurable entanglement in the near-threshold regime of the parametric amplification experiments. In addition, a type of near-threshold universal spatial entanglement has been identified in a planar parametric amplifier [7].

The challenge to generate and detect any macroscopic quantum entanglement in these macroscopic fields still remains however. In practice some loss is unavoidable, and the sensitivity of pure macroscopic superposition states to decoherence poses a significant problem to their detection. At best one would hope for a mixture of both microscopic and mesoscopic (or macroscopic) superpositions.

We have derived criteria for the detection of macroscopic quantum superpositions that are based on the measurable variances of output probability distributions. The criteria are applicable to both discrete and continuous variable measurements, and to macroscopic quantum entangled states that are of current interest experimentally, namely the two-mode squeezed state and the higher-spin and atomic squeezed states. We have shown how these new signatures give a macroscopic version of the Einstein-Podolsky-Rosen paradox and a Schrödinger's paradox, through the proven failure of certain macroscopic quantum mixtures. The work has been presented as part of two invited papers and is now published [8], with further papers submitted for publication.

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Quantum information

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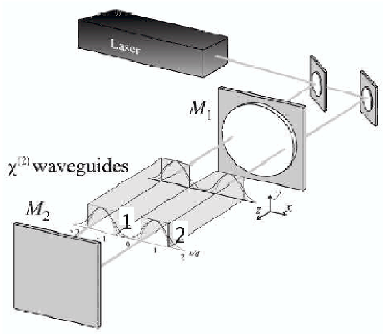
This research studies entanglement and states which exhibit the Einstein-Podolsky-Rosen (EPR) paradox, both central to quantum mechanics [1]. In the first system quantum correlations are evident at different spatial locations, leading to spatially entangled modes similar to those studied at the ANU Node of ACQAO in the context of quantum noise limited measurements for the Quantum Imaging project. This system is compatible with integrated optics techniques, and may provide a more robust source of spatial entanglement than interferometers that use discrete optical components. An experimental realisation of this device would be possible as part of the spatial entanglement and quantum imaging project at the ANU Node, using techniques that are already well understood. The second system studied is a potential source of continuous variable bright tripartite entangled beams, which have applications in quantum communication and teleportation.



The first system is two evanescently coupled $\chi^{(2)}$ parametric downconverters inside a Fabry-Perot cavity [2, 3], providing a source of quadrature squeezed light, Einstein-Podolsky-Rosen correlations and bipartite quantum entanglement, tunable by adjusting the coupling strengths and the cavity detunings. The spatial separation of the output modes means that they do not have to be separated by optical devices before measurements can be made, avoiding a possible source of loss. The entangled beams produced can be degenerate in both frequency and polarisation.

We also analysed a proposal by Pfister *et al.* [4] which used triply concurrent $\chi^{(2)}$ nonlinearities to produce bright beams which exhibit tripartite entanglement. We extended the original proposal to give a full quantum treatment of the operation of the device inside a pumped Fabry-Perot cavity, in both the above and below threshold regimes [5]. Above threshold strong tripartite entanglement was predicted for beams with macroscopic intensities. We also showed that there are two ways that the system can exhibit a three mode form of the Einstein-Podolsky-Rosen paradox, and calculated the extra-cavity fluctuation spectra that may be measured to verify our predictions. The continuous variable tripartite entanglement available from devices using twin nonlinearities was also analysed [6], with a comparison being made between concurrent and cascaded nonlinearities.

The quantum features of the nondegenerate optical parametric oscillator with injected signal were also analysed, with special attention being paid to the entanglement properties [7]. We found that signal injection can help to produce macroscopically intense entangled beams without the need for stabilisation above the usual oscillation threshhold.

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Theory of Double-Well BEC Interferometry

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Double-well atom interferometers (DWAI) based on the splitting of a single-well potential into two wells, evolution of quantum states due to an applied spatially-asymmetric potential and then recombination into the original potential well have been studied extensively. For double wells, near degenerate ground and excited states occur, and measurements of transitions between these states could be used to study the effect of the spatially-asymmetric potential. Such atom interferometers involve quantum interference between transition amplitudes for processes via intermediate states localized in the two separate wells. DWAI are well suited to implementation on atom chips [1], where micron scale dimensions of atom optical elements could allow precise control over the splitting and recombining processes. Such DWAI can be based on cold atomic gases, where each atom behaves independently, but for bosonic atoms they could be based on BECs. In the BEC case a macroscopic quantum system is involved, with all atoms occupying the same state. Large improvements in sensitivity over the single atom case may occur, similar to optical interferometry for laser light compared to thermal light.

A theory of BEC interferometry in an unsymmetrical double-well has been developed [2] using the two-mode approximation, where the bosonic atoms are restricted to only occupying two modes. This approach is valid for small atom numbers, where the mean field energy term is much less than the vibrational energy quantum for the trap. Self-consistent equations for the two condensate mode functions and the amplitudes of Fock states describing possible fragmented condensates have been obtained using variational principles. The former are generalized Gross-Pitaevskii equations. In a Bloch sphere variant of the theory, the BEC is treated as a giant spin system, the fragmented states are eigenstates of S^2 and S_z . Interferometric effects may be measured via the boson numbers in the first excited mode.

A more general theoretical treatment of DWAI using BEC is also being developed using the stochastic gauge theory approach [3] of our ACQAO collaborators at University of Queensland. This allows for large boson numbers and for decoherence effects (which can degrade the interference patterns) due to quantum fluctuations around the condensate wavefunction, thermal effects, random fluctuations in magnetic fields, etc... Partial differential equations for stochastic fields will be obtained, with deterministic terms equivalent to the Gross-Pitaevski equation for the condensate wavefunction and with stochastic noise terms representing various decoherence effects.

A general theory of decoherence effects in macroscopic quantum systems has also been formulated [4], relating the fidelity loss to the quantum state and to Markovian relaxation rates. The approach could be applied for decoherence effects in double-well BEC interferometry.

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Generation of matter-wave gap solitons in optical lattices.

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The first experimental generation of bright gap solitons in a Bose-Einstein condensate with repulsive atomic interactions was achieved in 2004 [1]. This counter-intuitive "self-focusing" of a BEC is possible due to anomalous dispersion properties of the matter wave in a periodic potential of a 1D optical lattice.

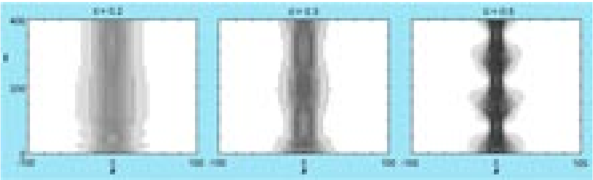

Figure 1: Managing matter-wave dispersion in an optical superlattice: localization length of the repulsive BEC wavepacket varies as the superlattice parameter ε is changing. The case $\varepsilon \to 0$ correponds to a single-periodic lattice; for $\varepsilon \neq 0$ modulation of well depth at double-period appears; the period doubles as $\varepsilon \to 1$.

The generation procedure [1] involves loading the condensate into a ground (Bloch) state of the optical lattice and adiabatic acceleration to the band edge. Our aim was to model this process using the 1D mean-field Gross-Pitaevskii equation for the condensate wavefunction. We have demonstrated that the efficiency of the gap soliton formation can be greatly improved by preparing the the initial state via interference of two BEC wavepackets counterpropagating at quasi-momenta corresponding to the opposite edges of the same Bloch-wave gap [2].

The shape of a gap soliton can be controlled through matter-wave dispersion management (Fig. 1). This involves modifying the curvature of the spectral bands and is possible in systems that allow fine-tuning of the band-gap properties in the wide range of parameters. We found that optical double-period superlattices represent an ideal system for the dispersion management due to high sensitivity of dispersion at the edges of Bloch-wave minigaps to the shape of the superlattice potential [2].

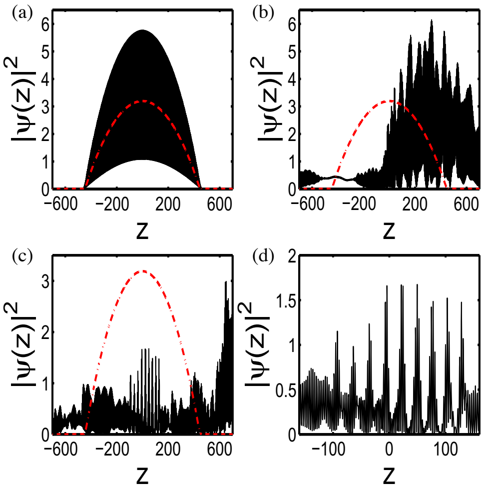

Figure 2: Formation of solitons from a modulationally unstable inhomogeneous Bloch state. Shown are BEC density profiles (a) at the start (red) and at the end of the lattice ramp-up time; (b) at the end of acceleration to the band edge; (c) after evolution at the band edge and (d) close-up showing the soliton train.

Nonlinear dynamics of the matter-wave Bloch states at the edge of a Brillouin zone can provide an alternative method for generation of gap solitons through the development of modulational instability. By using the non-polynomial mean-field model, we demonstrated that the recently observed instability of the Bloch states of a repulsive Bose-Einstein condensate in a moving one-dimensional optical lattice [3] can lead to dynamical localization of a condensate in the form of gap soliton trains. We studied the characteristic features of the localization under realistic experimental conditions, including the process of adiabatic loading and acceleration to the band edge (see Fig. 2). A paper summarizing our results is being prepared for submission. Currently, in collaboration with the ACQAO theory node at the University of Queensland (M. Davis and A. Bradley), we are investigating the influence of the finite temperature effects on the dynamics of Bloch states and formation of soliton trains.

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M. Colla, Hans-A. Bachor Proceedings editors 'Congress Handbook and Abstracts' *16th National Congress 2005 Australian Institute of Physics ISBN 0-9598064-8-2*

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PERSONNEL AND ASSETS

The greatest resource for our research is people. 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 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 effective administrative team (see below — Ruth Wilson COO, Max Colla at ANU, Tatiana Tchernova at SUT, Linda Schumacher at UQ, Wendy Quinn (IAS) has responsibility for the financial and organisational work, creating more time for research.

We have been able to attract excellent additional staff. We are particularly proud that we have attracted talented Australians who have worked overseas back to Australia. In 2005 Hui He has joined UQ and Oliver Glöckl the ANU. At the same time several excellent students have chosen ACQAO for their PhD program and we are actively seeking to increase our graduate student program. A full list of the complete ACQAO staff is given on page 54.

The other big asset is our research laboratories. We started with excellent facilities at SUT and ANU for one project. We have built new, custom made laboratories in the ANU IAS and the Faculties for new projects.

New ACQAO laboratory at ANU Faculties

In 2004 we purchased a major piece of equipment, a frequency doubled Ti-Sapphire laser (total cost $498.000) which was installed at the ANU and a wide range of additional equipment at all nodes. Our total equipment purchases make up about 30% of our entire budget. All of our experiments have gained significantly from a wide range of new equipment, which makes our work competitive on the global stage.

In 2005 the Centre obtained a LIEF infrastructure grant, to purchase advanced RF electronic equipment which will be shared between the ANU and SUT nodes, and a research team on another BEC project outside the Centre at UQ.

L to R: Peter Hannaford, Ken Baldwin, Robert Ballagh (Otago University), Hans-A. Bachor, Crispin Gardiner (Otago University), Andrew Wilson (Otago University), Peter Drummond

Collaboration and Linkage

Throughout the year 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:

- Paris on quantum imaging and atom laser development with two cotutelle projects (V. Delaubert and J. Dugue) have been established, and staff have been exchanged (C. Fabre, Hans-A. Bachor)
- Hannover on BEC-on-a-chip and optical entanglement where a joint PhD program (F. Scharnberg) has been completed and staff have visited (M. Heurs, Hans-A. Bachor)
- London on BEC-on-a-chip where we exchanged expertise through visits (E. Hinds, B. Hall, P. Hannaford).
- Erlangen on optical entanglement where we exchanged staff (O. Glöckl)
- Amsterdam and Paris where we exchanged expertise between the three He* BEC experiments (K. Baldwin, W. Vassen, M. Leduc).
- Dunedin and Auckland where we have started a joint project (M. Davis, B. Blakie) and held successfully a joint conference and workshop in Queenstown.

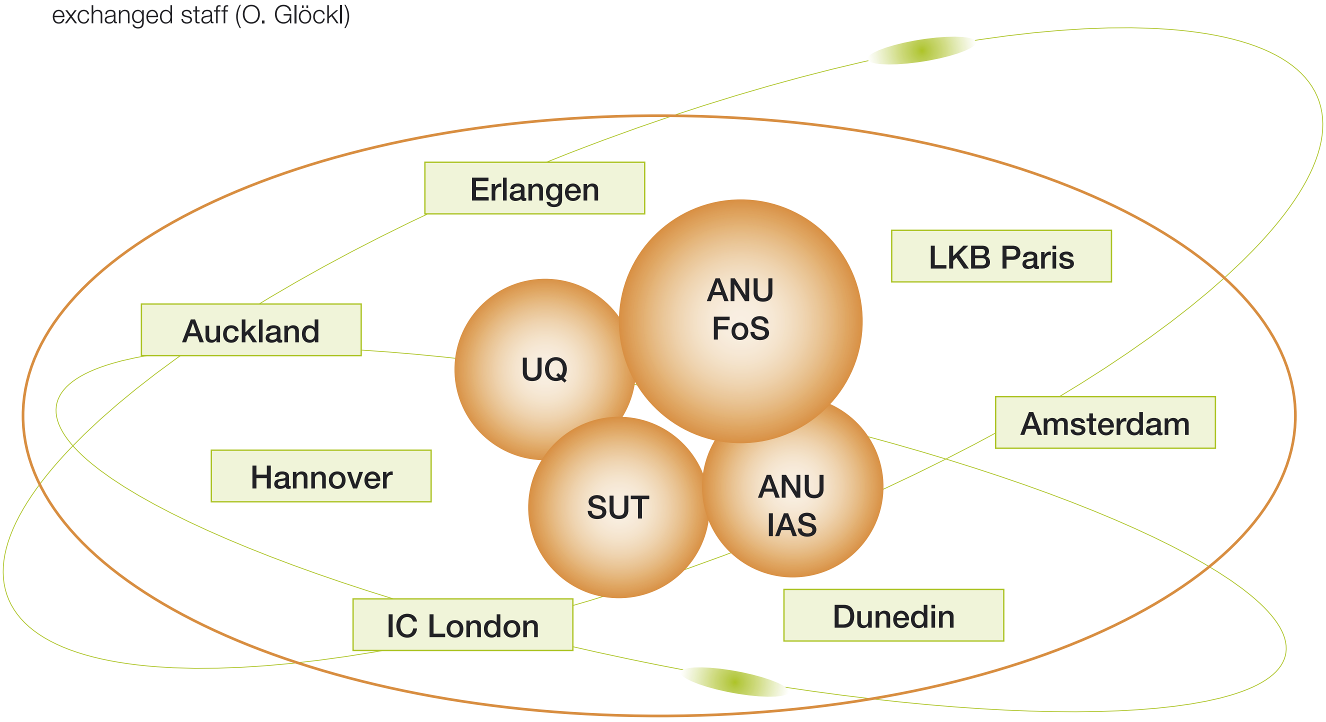
Additional intensive collaborations include:

de Physique Théorique et modèles statistiques, Université Paris — SUD XI for the development of new theory G. Shlyapnikov, K. Kheruntsyan & P. Drummond)

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

Texas University on the question of transition from atomic to molecular BECs (D. Heinzen, P. Drummond, K. Kheruntsyan)

Universität Innsbruck with exchange visitors in the area of molecular BECs (M. Bartenstein and G. Duffy).



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

ACQAO team at Le Houches, France

All of these exchanges bring expertise to Australia, enhance our international profile and in several cases have led to joint publications listed on page 42. At the moment we are investigating the options for ACQAO participation in European research networks.

We have signed a contract with the Sonderforshungsbereich in Hannover and the CNRS/IFRAF France to organise annual quantum atom optics workshops over three years — one in each country. In February 2005 we took part and helped to organise the Quantum Atom optics workshop in Les Houches. In December we organised a joint workshop at Queenstown, New Zealand with our partners in Dunedin and Auckland. These workshops provide unique opportunities for our students and staff to meet their peers, to discuss science and visit other laboratories.

Participants at New Zealand Workshop in Queenstown

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.

Commercialization

While our research projects focus entirely on strategic fundamental research, 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.

We have received funding of $250,000 from the ACT Government to commence research and start commercialisation activities in Canberra. We are using these funds for three projects where we are supporting the development of a new, economical technique for locking the frequency of a tunable laser to an atomic transition. In 2005 J. Close, N. Robins and their collaborators have applied for a provisional patent and are presently investigating the opportunities for commercial interest in this laser locking technique.

The second project is being carried out by K. Baldwin and A. Truscott who will develop a practical instrument for the measurement of the phase of coherent atoms. The third project, led by C. Harb, investigates ways of producing high efficiency second harmonic generators. We are negotiating a research link to a US laser manufacturer. 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.

KEY PERFORMANCE INDICATORS (KPI)

We believe that 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.

We have a thriving theory core that produces results at an increasing pace. At the same time we are rapidly approaching the completion of the building phase for our experimental projects — and most of them are already producing impressive results. All these outcomes are described in the Science section (pages 7–41) of this report.

For 2005 we have exceeded the projected KPIs with 42 publications. Amongst these are 4 publications with particularly high impact factor in *Phys.Rev. Letters*. We are proud of the impressive impact our publications have, as measured by actual citations.

We succeeded in recruiting many new postgraduate students (12) and have a steady rate of postgraduate completions (2). The number of Honours students (6) is above our target.

We have exceeded our goals in regard to the number of visitors who came to Australia (21) to see our work and the number of invitations (22) we received to address international conferences. We are seeing longer and more intensive exchanges of students and staff internationally, indicating our increasing visibility. At the same time we are creating more collaborations within the Centre.

We have formed an active international student network with our partners in Paris and Hannover to organize international meetings and we held a workshop jointly with our partners in New Zealand.

At the same time, we have maintained a widespread teaching program at all three Universities, with a total of 22 undergraduate and 8 professional courses in 2005. We have presented our ideas and goals to a wide section of the Australian Physics community. This includes the organisation of the National Congress of the Australian Institute of Physics and many public lectures.

Awards

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

Yuri Kivshar was awarded the Walter Boas Medal of the Australian Institute of Physics. The aims of the award are to promote excellence in research in Physics in Australia and to perpetuate the name of Walter Boas.

Warwick Bowen was awarded the Bragg Medal by the Australian Institute of Physics for the best PhD thesis in Physics in 2004. He was also awarded the Crawford prize for the best Science PhD thesis at the Australian National University in 2004.

The ARC awarded Centre Fellowships to Joseph Hope and Karen Kheruntsyan for their excellent contributions to ACQAO.

Ken Baldwin has been appointed Director at Large on the Board of the Optical Society of America.

Elena Ostrovskaya was awarded a grant from the ANU career development assistance fund and a travel grant from the Australian Academy of Science.

Beata Dabrowska and Sebastian Wüster were awarded travel funds by the Australian Institute of Physics.

Prof Hans-A. Bachor presents Warwick Bowen with the Bragg Medal

Key Performance Indicators (KPI)

Key Result Area	Performance Measure	Target	Outcome
Research Findings	Quality of publications International Ref. Journals with an impact factor >5	3/20	4/42
	Number of publications/year	20	42
	Number of patents/year	0.3	1
	Number of invitations to address and participate in international Conferences/year	4	22
	Commentaries in professional journals National and international/year	3	4
Research Training and Professional Education	Number of postgraduates recruited/year	5	12
	Number of postgraduates completions/year	4	2
	Number of Honours students/year	5	6
	Number of professional courses to train non Centre personnel/year	2	8
	Number and level of undergraduate and high school courses in the Priority area/year	7	22
International, National and Regional Links and Network	Number of International visitors/year	10	21
	Number of national and international workshops/year	1 international 1 national	2 1
	Number of visits to overseas Laboratories	18	74
	Contact with researchers related to the philosophical aspects of Quantum Physics	2	1
End-user Links	Number and nature of commercialisation activities	2	1
	Number of government, industry and business briefings/year	2	1
	Number of Centre associates trained In technology transfer and commercialisation	2	1
	Number and nature of Public Awareness programs	4	8

OUTREACH/MEDIA

Outreach is an important mission of the Centre — our goal is to explain quantum and atom optics to the widest possible audience. 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 300 students and 30 teachers.

In February 2005 many members of ACQAO, led by K. Baldwin and Hans-A. Bachor, helped organise the AIP Congress with the title "Physics for the Nation" in Canberra. This was the curtain raiser for the International Year of Physics in Australia and was also an opportunity to raise the awareness for quantum technologies and physics research as a whole. A summary of the media coverage is given below.

Prof Hans-A. Bachor with "Einstein" at the AIP Congress

The International Year of Physics continued throughout 2005 with a series of public talks, which featured P.K. Lam, J. Close and Hans-A. Bachor in Canberra and P Drummond in Brisbane. Hans-A. Bachor gave a keynote presentation on the Metrology Society of Australia 2005 conference and presented the inaugural teaching colloquium at the National Measurement Institute and a series of other colloquia around the country. In addition, both P. Hannaford and P. Drummond presented lectures on ACQAO work to the AIP in Melbourne.

Many members of our Centre attended international conferences. We used these opportunities to present quantum science to wide audiences, ranging from school classes in Germany and Singapore (Bachor) to official government contacts in Japan (Baldwin).

Dr Ken Baldwin, Chair of the International Council for Quantum Electronics greets the Crown Prince of Japan at IQEC 2005, Japan

ACQAO is a corporate member of the AOS, and is represented on the Board of AOS, OSA and AIP. The Centre has sponsored invited speakers to the AIP Congress and the ACOLS conference.

Our COO, R. Wilson is maintaining an active PR program and we are using the opportunities to publicise our latest results in the media.

Ruth headed the media team for the AIP Congress, and reports that the following media on Physics was achieved in 2005:

Television:	
National	2
Metropolitan	2
Print:	
National	2
Metropolitan	15
Radio:	
National	2
Metropolitan	4

Prof Peter Hannaford talks with Prof Gerd Leuchs at the Nobel Prize festivities in Stockholm

Australian Personal Computer Magazine featured an article on Technology in the New Millennium involving an interview with K. Baldwin on ACQAO work with BECs. (See extract "Quantum Soup" below.)

Quantum Soup

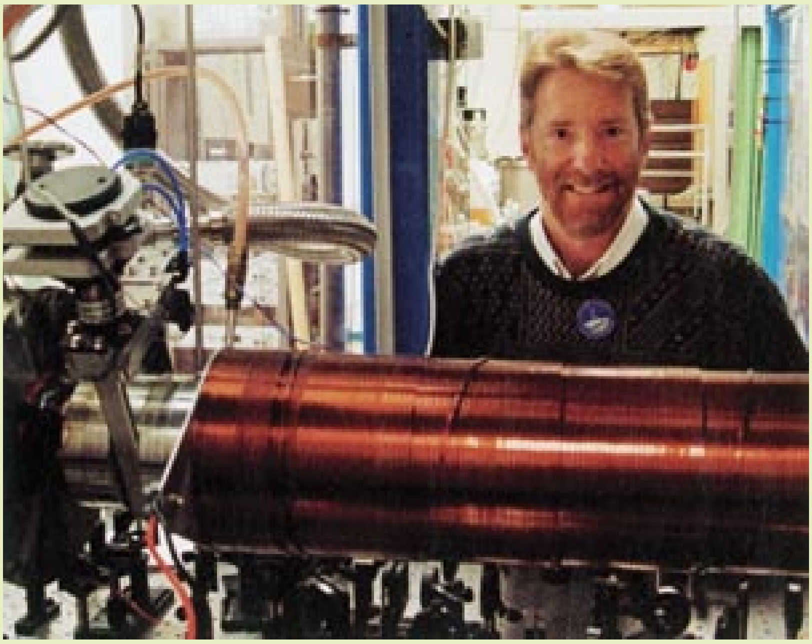
While some researchers wrestle with the complexity of building quantum computers, other teams are turning quantum's strange properties towards replicating different parts of the information world. For example, a team at the ARC Centre of Excellence for Quantum-Atom Optics (ACQAO), headquartered at ANU, is exploring the use of Bose-Einstein condensates (BECs) to create a form of quantum storage (not to be confused with the decidedly non-quantum "Quantum" hard drives in millions of PCs).

A BEC is a physical anomaly created when a number of discrete particles are stored in a vacuum that is cooled to near absolute zero. Fundamental laws of thermodynamics dictate that the cooler the system, the slower the particles will move. Gravity eventually takes over, and the particles accumulate at the bottom of the confining potential.

It's impossible for the particles to stop altogether: this would only happen at a temperature of absolute zero, and would violate physicist Werner Heisenberg's uncertainty principle, which says that we can never actually measure the location of an electron but can only predict in which area it will move. However, through the same quantum interactions discussed earlier, increasingly dense and slow-moving particles begin to coalesce into a kind of quantum "soup" (the BEC).

"We are taking all the concepts that have already been proven in quantum optics and moving them one stage further with atom or matter waves, rather than light waves," says Dr Kenneth Baldwin, ACQAO's deputy director. "We want to separate the atom's electronic wave functions so they don't interact, but we make them so cold that their centre-of-mass wave functions are so large that they overlap and become one macroscopic quantum state."

The resulting soup is remarkably homogenous in its composition, and this fact has driven the ANU team to look at ways in which it could be exploited to create a form of quantum storage. Their current work revolves around using the interference of light waves to create a regular, structured lattice that could trap quantum particles in a form of storage medium — much like a farmer's plough separates rows of plants so that contaminants run down into furrows.



Dr Kenneth Baldwin, ACQAO's Deputy Director

BECs are very low-density concoctions (so storage density would be low), but since we're talking about atom-scale here rather than ferromagnetic storage — as on hard drives — it could still be denser than existing storage methods.

As if turning BECs into a storage lattice wasn't difficult enough, the ACQAO team is now tackling the even trickier bit: controlling the electrons on the atoms. This can only be accomplished using a laser with a frequency and bandwidth that relate to the type of atoms being used. Fur this reason, they're using rubidium atoms and a rubidium-tuned laser (which functions like the read/write head on a hard drive).

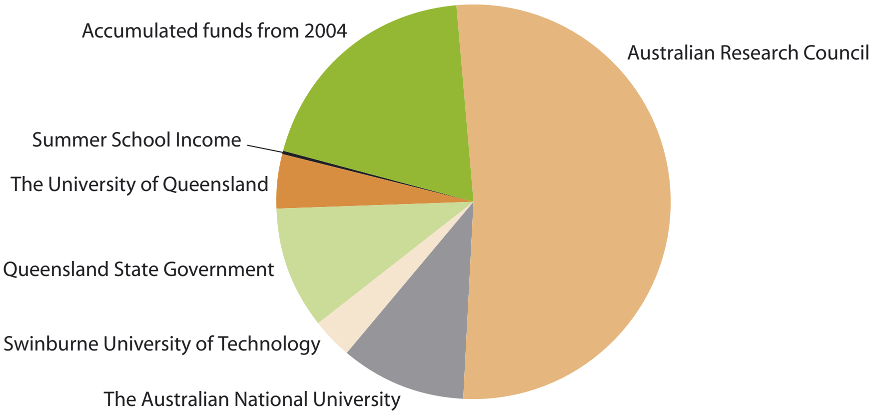
Just as in quantum computing, decoherence is the enemy of quantum storage: the lasers not only need to be able to write the information onto the rubidium atoms, but need to do so quickly and effectively enough that the data storage is not lost to decoherence. So far, says Baldwin, experiments in storing light in a rubidium gas have managed to stretch the delay time in the atomic vapour to above two microseconds, which is somewhat less than the coherence time in the system. The team's hope is to extend this to ultra-cold gases with much longer storage times.

The rubidium laser work is only one of the projects currently underway at ACQAO. One project is exploring the use of a magnetic room-temperature microchip to create a storage lattice in a near-absolute-zero BEC suspended just nanometres above the chip. Another group at ANU is examining the use of quantum electron manipulation techniques on other types of atoms — for example, information could be stored in the highly structured carbon lattice of diamonds by creating tiny atomic defects in the lattice. These and other projects around the country are all contributing to the advancement of quantum computing techniques, and the unified community has helped Australia punch well above its weight in terms of real quantum computing research progress.

"All of these research streams feed into each other in a way that allows us to make progress in ways we might not have had if all these projects were running independently," says Baldwin. "Physicists have come a long way, and I think we're homing in on the quantum computer. It's not going to happen immediately, but the timeframe, over which it's likely to become technological reality, is shortening."

ACQAO INCOME 2005

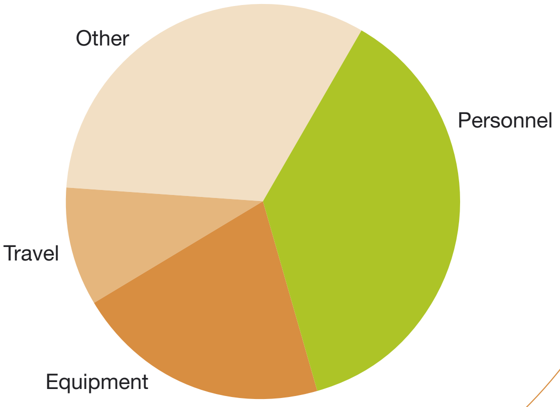
Accumulated funds from 2004	$874,675.00
Australian Research Council	$2,342,424.00
The Australian National University	$456,000.00
Swinburne University of Technology	$150,000.00
Queensland State Government	$450,000.00
The University of Queensland	$207,090.00
Summer School Income	$1,817.00
TOTAL INCOME	**$4,482,006.00**



Note: The Queensland State Government funding for 2003, 2004 and 2005 was forwarded in one total payment of $450,000 during the year 2005.

ACQAO EXPENDITURE 2005

Personnel	$1,117,218.00
Equipment	$631,736.00
Travel	$284,965.00
Other	$966,292.00
TOTAL EXPENDITURE	**$3,000,211.00**



ACCUMULATED FUNDS	**$1,481,795.00**

ACQAO 2005 PERSONNEL

Below is a list of all Staff and Students including Honours/Undergraduates with project work in ACQAO during 2005.

ANU FAC Node

Prof Hans-A. BACHOR
Dr John CLOSE
Mr Max COLLA
Mr Neil DEVLIN
Dr Cristina FIGL
Dr Oliver GLÖCKL
Dr Charles HARB
Dr Joe HOPE
Dr Mattias JOHNSSON
Dr Ping Koy LAM
Dr Laurent LONGCHAMBON
Dr Nick ROBINS
Dr Craig SAVAGE
Ms Ruth WILSON
Mr Thomas ARGUE
Mr Vincent DELAUBERT
Mr Julien DUGUE
Mr Simon HAINE
Mr Gabriel HETET
Mr Magnus HSU
Mr Mat JEPPESEN
Mr Mikael LASSEN
Ms Adele MORRISON
Ms Amy PENG
Ms Katie PILYPAS
Mr Sebastian WÜSTER

ANU IAS Node

Dr Ken BALDWIN
Dr Tristram ALEXANDER
Dr Robert DALL
Prof Yuri KIVSHAR
Dr Chaohong LEE
Dr Elena OSTROVSKAYA
Ms Wendy QUINN
Dr Andrew TRUSCOTT
Ms Beata DABROWSKA
Ms Pearl LOUIS
Mr Andre STOFFEL
Mr Santiago CABELLERO

UQ Node

Prof Peter DRUMMOND
Dr Ashton BRADLEY
Dr Joel CORNEY
Dr Matthew DAVIS
Dr Hui HU
Dr Karen KHERUNTSYAN
Dr Xia-Ji LIU
Dr Murray OLSEN
Dr Margaret REID
Mr Clinton ROY
Ms Linda SCHUMACHER
Mr Paul SCHWENN
Mr Eric CAVALCANTI
Mr Andy FERRIS
Mr Chris FOSTER
Mr Scott HOFFMANN
Mr Tim VAUGHAN

SUT Node

Prof Peter HANNAFORD
Dr Bryan DALTON
Dr Grainne DUFFY
Dr Brenton HALL
Ms Sharon JESSON
Prof Fel Tien KIEU
Prof Fel Russell MCLEAN
Dr Wayne ROWLANDS
Prof Fel Andrei SIDOROV
Ms Tatiana TCHERNOVA
Mr Russell ANDERSON
Mr Paul Dyke
Mr Jürgen FUCHS
Mr Saeed GHANBARI
Mr Heath KITSON
Mr Falk SCHARNBERG
Mr Mandip SINGH
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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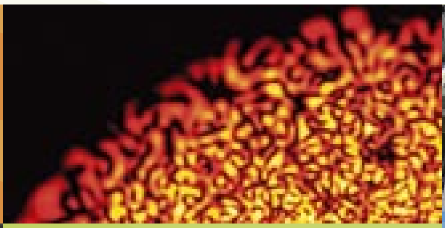

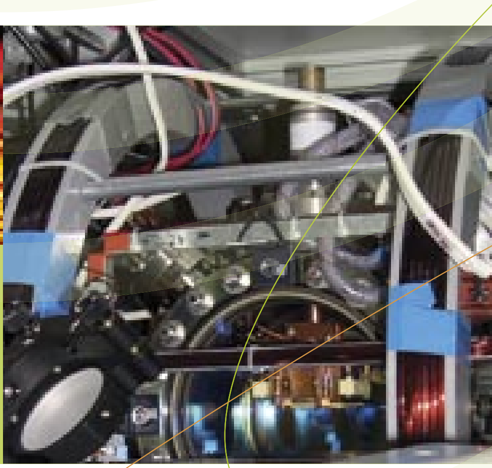

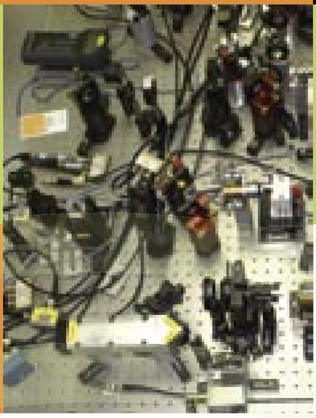

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