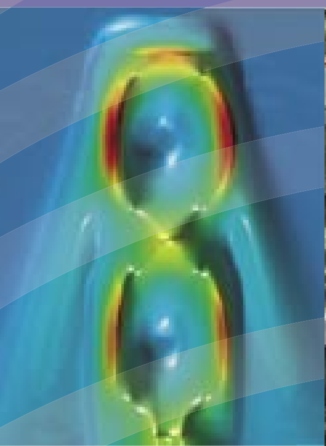
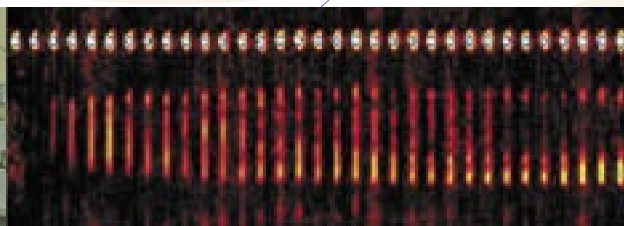




The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report 2005

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

SWINBURNE
SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian Government
Australian Research Council

CONTENTS

FOREWORD

Professor Hans-A. Bachor

Quantum science will play a major role in future technology and eventually our daily lives. Our focus is 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 world of classical. Technically we are now able to use the process of entanglement, 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 and atom lasers. Combining these we are at the threshold of turning fundamental science into practical applications over the next two decades.

The Australian Research Council Centre of Excellence for Quantum-Atom Optics (ACQAO) is one of Australia's main contributions 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.

ACQAO combines the 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 the close interaction that we develop, ensures that Australia can make major contributions internationally.

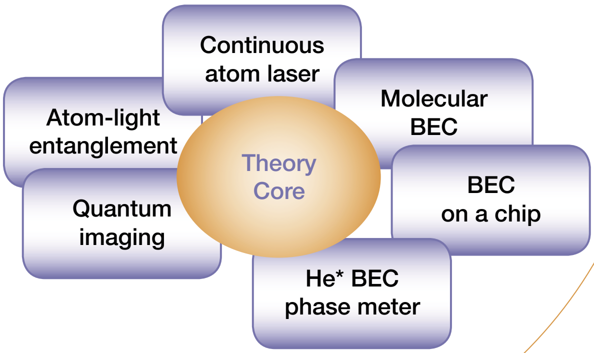
Our Centre is part of the vision of the ARC to promote excellence in the most successful fields of research and to give them the opportunity to become players in the international arena. We have established and extended close research partnerships with six centres in Europe and two in New Zealand. The 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 second annual report, describes the structure of the Centre, the staff, our research plans and our achievements in 2004. You will see from the science reports that we have major advances in all our experiments, and have enhanced the involvement of our strong theoretical core. This will allow us to accelerate 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 some of the technologies of the future.

Hans-A. Bachor

Hans-A. Bachor
Research Director

QUANTUM-ATOM OPTICS



Our research goals

Light as Particles and Atoms as Waves

In optics we consider the propagation and effects of light in the form of electro-magnetic waves. Interference fringes are a typical result of this type of classical optics. In contrast, quantum optics adds to this the effects based on the quantisation, or particle nature, of light. It has become easier over the years to isolate such quantum effects and they appear more and more frequently as a limit on 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 is essentially based on classical optics, will benefit soon from the advances in quantum optics. Australia has long held a strong international research profile in this field, in particular experiments using continuous laser beams.

Entanglement

Entanglement is one of the key concepts of quantum physics. It describes the properties of two systems which originate from one source and are, in the ideal case, indistinguishable. For example these could be two laser beams propagating in different directions, created in one source and which contain identical information, modulation and noise. The ANU researchers have already built sources which 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 have reported impressive new results, through the first demonstration of a two dimensional laser pointer.

Atom Optics

Atom optics, by comparison, is a field where we find that atoms not only have the properties of particles that can 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. It has been shown some years ago that the de Broglie waves of the atoms can be made to interfere, which allows whole new types of precision instruments, namely atom interferometers. These can be developed into very sensitive sensors, for example for measurements of the earth's gravitational field. In addition 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 the so-called Bose-Einstein Condensate (BEC) which has properties vastly different from a thermal cloud of individual atoms.

Bose-Einstein Condensate

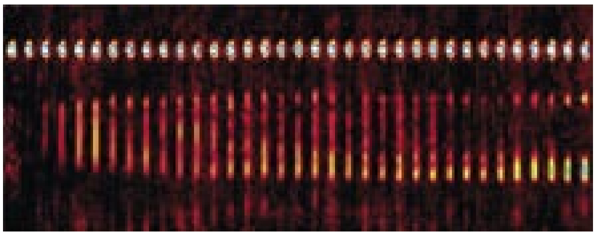
Within the Centre we have, since July 2003, the first apparatus in Australia to generate a BEC. At the time of publishing this report, we have a second, very compact BEC on a chip at SUT (see page 15), based on a unique technology using permanent magnets with micron sized structures to trap the atoms. These devices should allow us to build small, reliable BEC instruments which can be developed into robust and very sensitive sensors, based on atom interferometry.

In addition we want to extend the work in Europe and produce a BEC from metastable Helium (He*) atoms. At the ANU we have extensive experience in generating, collimating and trapping He* and we have experience in detecting individual He* atoms. Our goal here is to build a measurement system for the development of the atomic phase within a He* BEC.

We also want to extend the generation of a BEC from atoms to molecules at SUT. First results were recently reported in Europe and the USA on condensing molecules. We wish to perfect this technique and demonstrate some of the novel correlation effects, predicted in theories created by members of the Centre.

Atom Laser

An extension of the BEC work is to create an atom laser, a machine that produces a coherent beam of atoms, in analogy to an optical laser. Late in 2004, we extended our studies on the pulsed atom laser to the quasi-continuous regime and made the first measurements on noise and flux in this system. This knowledge is critical if the atom laser is to become a practical device in applications. Very recently we produced and have made initial studies of the first Raman out-coupled atom laser. This device looks promising as a means of increasing the flux of the beam.



Pulses from the atom laser

Linking Quantum and Atom Optics

This Centre combines, in a unique way, quantum optics and atom optics. We transfer ideas from one area to the other. Experimentally we plan to do this by building an apparatus that can transfer the entanglement from the light to atoms and vice versa. This would be an initial step in designing a storage for quantum information.

Complementary experiments on quantum information communication and cryptography are carried out independently at ANU outside the Centre in collaboration with members of the Centre for Quantum Computing Technology.

All these experimental goals are complemented by a very strong theory core, which combines the expertise of world renowned researchers at UQ and ANU. 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 ahead of the experiments and we have projects, such as the relationship of Bosonic systems at low dimensions, the matter wave properties of optical lattices and the formation of 3D solitons in coupled atomic-molecular BECs, which can lead us to unique experiments.

Scientific tools for the future

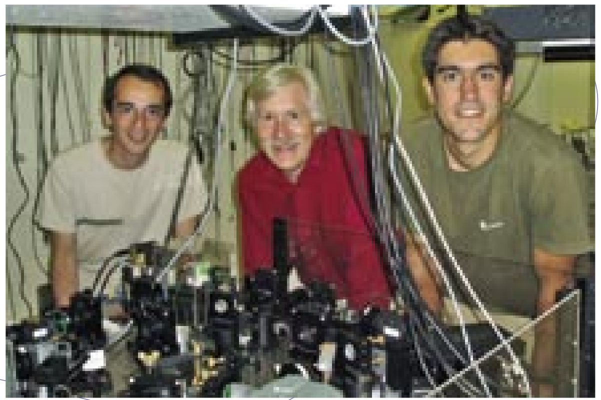
The goal of the Centre is to provide the scientific tools required to develop quantum and atom optics into a whole new field of optical quantum technology. These include ideas, experimental demonstrations and simulations. This work over the next five years prepares the way for applied work in quantum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

The Centre does this by combining the separate concepts of quantum and atom optics, by linking the leading scientists in Australia and by developing an exchange with our partners in Europe and New Zealand who are in some of the most productive groups in this field. In this way the Centre is present in the international arena and ensures that quantum technology will be 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 remain in their individual locations, in Canberra, Melbourne and Brisbane, but are linked through joint scientific projects, the sharing of expertise and equipment and the exchange of people.

The Centre is coordinated from the Australian National University (ANU) by the Research Director, Hans-A. Bachor and the Chief Operations Officer (COO, Ruth E Wilson). The science is carried out by a theory core group and six experimental projects established by the 22 CIs who founded the Centre. The scientific goals have been chosen to be ambitious, moving forward the present frontiers of knowledge in quantum and atom optics by employing the expertise from all members of the Centre



L to R: Nicholas Treps, Hans-A. Bachor, Vincent Delaubert

ANU FAC, Canberra

Back row L to R: Simon Haine, Katie Pilypas, Mattias Johnsson, Hans-A.Bachor, Sebastian Wuester, Craig Savage, Cristina Figl, Nick Robins
Front row L to R: Max Colla, Charles Harb, Ping Koy Lam, Ruth Wilson, Laurent Longchambon, Adele Morrison

At the ANU we have the research node which carries out experimental work with the Rb BEC and atom laser, including the development of new diagnostic techniques (John Close, Nick Robins, Cristina Figl). This node also undertakes experiments on quantum imaging, spatial entanglement (Hans-A. Bachor, Charles Harb) and tuneable entangled light, atom and light entanglement and storage of quantum correlations (Ping Koy Lam). This is complemented by advanced theory (Joe Hope, Craig Savage, Mattias Johnsson) that concentrates on the properties of coherent atom sources, quantum feedback and macroscopic quantum effects.

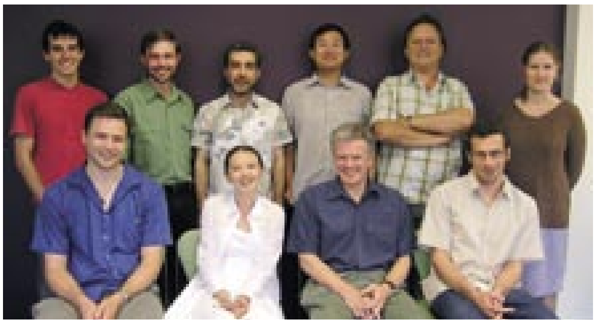
ANU IAS, Canberra

At the other side of the ANU, 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. A new laboratory has been established for the 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). We have a theoretical group which has world leading experience in non-linear optics, optical lattices and soliton physics (Yuri Kivshar, Elena Ostrovskaya, Tristram Alexander, Chaohong Li) and their focus is on the properties of matter waves in optical lattices.

L to R: Chaohong Li, Elena Ostrovskaya, Yuri Kivshar, Wendy Quinn, Tristram Alexander, Beata Dabrowski, Pearl Louis

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

UNIVERSITY OF QUEENSLAND, Brisbane



Back row L to R: Eric Cavalcanti, Joel Corney, Karen Kheruntsyan, Hui Hu, Murray Olsen, Margaret Reid
Front row L to R: Matthew Davis, Xia-Ji Liu, Peter Drummond, Ashton Bradley

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, Lia-Ji Liu and Margaret Reid). Their work includes the numerical and quantum phase-space methods for the simulation of BECs, cold molecule formation, quantum correlations in one dimensional Bose and Fermi gases, fundamental tests of quantum mechanics, and the development of dedicated software. The theory work connects to many aspects of the experimental projects in all the other nodes.

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 microfabricated permanent magnet structures which will be used to produce BECs on a chip (Andrei Sidorov, Russell McLean and Brenton Hall). In parallel, an experiment for the generation and condensation of Li molecules is in preparation (Wayne Rowlands and Grainne Duffy). A small theory group complements this work (Bryan Dalton, Tien Kieu).

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 42. The administration includes research assistant Max Colla (ANU FAC) and Administrators Diane Hutton (UQ), Sharon Jesson (SUT) and Wendy Quinn (ANU IAS).

Jürgen Fuchs and Gráinne Duffy at Swinburne

Back row L to R: Holger Wolff, Russell McLean, Brenton Hall, Andrei Sidorov, Peter Hannaford, Alexander Alkushin, Shannon Whitlock
Front row L to R: Tien Kieu, Ruth Wilson, Saeed Ghanbari

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 (Coolum 6/2004, Canberra 12/2004). The ongoing administration is supervised by the Executive Committee, which meets four times a year. Node Directors are responsible for the continuous operation of the four nodes. Regular science meetings are held fortnightly within the nodes and we hold, given by demand, scientific discussions, brainstorming sessions and discussions which bring together members of the Centre from all locations (Canberra 3/2004, Coolum 6/2004, Kioloa 12/2004)

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.

We are fortunate to have an advisory board of exquisite expertise. Our international science advisors are world 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

Advisory Board Chair Prof Alain Aspect


Prof Keith Burnett, Prof Alain Aspect, Prof William Phillips, Prof David Pegg

Centre Management Meetings			
CI meeting	All CIs & COO	Bi-annual	6/04 Coolum 12/04 Canberra
Executive Committee	Res Dir. & COO Node Directors	quarterly	1/04 Canberra 4/04 Canberra 10/04 Melbourne
Advisory Board	International & national members	annually	12/04 Canberra
International Workshop	Centre & partners, other AUS groups	Bi-annual	12/04 Kioloa
Individual Project & group	Staff & students, visitors	fortnightly	
IP committee	Node directors, Universities	annually	

’Shut down’ of a continuous atom laser

N. P. Robins, A. K. Morrison, J. J. Hope, and J. D. Close
ACQAO, Faculty of Science, Australian National University, Australia

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)).

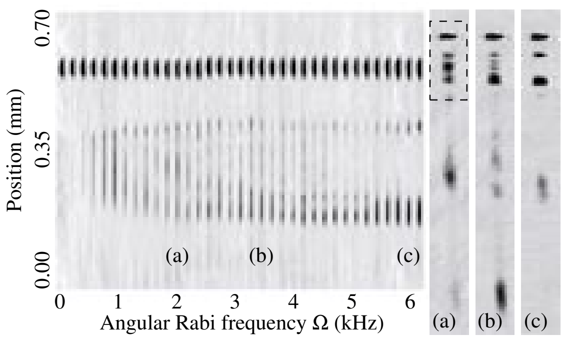


Figure 1: Optical depth plot (35 independent experiments) showing the spatial structure of a 3 ms atom laser as a function of output-coupling strength parameterised by the Rabi frequency. The system was left to evolve for a further 4 ms before the trap was switched off and 2 ms later the images were 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.

References

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A continuous Raman atom laser

N. P. Robins, A. K Morrison, C. Figl and J. D. Close
ACQAO, Faculty of Science, Australian National University, Australia

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 $4\hbar k$ 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 $4\hbar k \sin(45)$ downwards. We are currently pursuing quantitative studies of flux and fluctuations in this type of atom laser output-coupler.

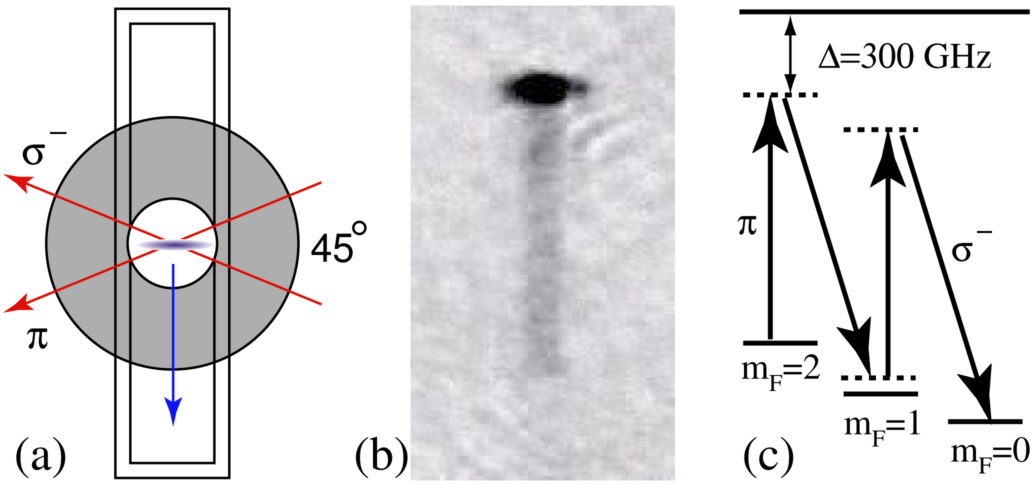

Figure 1. (a) Schematic diagram of the optical set up used for creating the Raman transitions, (b) Absorption image of an 8.5 ms continuous Raman atom laser produced with 40μW per beam, and (c) Transitions from the $5^2\mathrm{S}_{\frac{1}{2}}\mathrm{F} = 2, \mathrm{m_F} = 2$ state to the $\mathrm{F}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

References

[1] N. P Robins, A. K. Morrison, J. J. Hope and J. D. Close, cond-mat/0501747.
[2] E. W. Hagley *et al.*, Science **283**, 1706 (1999).

Theoretical atom laser dynamics

S. A. Haine, M. T. Johnsson, and J. J. Hope
ACQAO, Faculty of Science, Australian National University, Australia

The squeezed atom laser: We have theoretically investigated the possibility of creating an atom laser with non-classical output by outcoupling with squeezed light. We have developed a multimode quantum field model of an 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 almost completely the quantum statistics of an arbitrary optical state from one of the optical beams to the atom laser beam. This may be used to perform sub-shot noise measurements in atom interferometers, in the same way as optical squeezing squeezing allows more sensitive interferometric measurements. We have shown that two-mode optical squeezing as produced from an optical parametric oscillator can produce twin entangled atom laser beams propagating in different directions. We show that the fluctuations in the difference of the flux for our twin atom laser beams are suppressed by approximately a factor of eight compared to coherent atomic beams. This may prove to be an easy way to generate entangled atoms to test the behaviour of spatially separated, entangled massive particles.

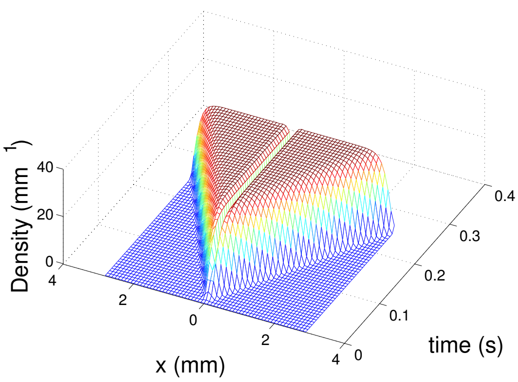

Figure 1: Twin atom laser beams produced from outcoupling atoms from a BEC using two-mode squeezed light. Beam correlations can be highly sub-Poissonian.

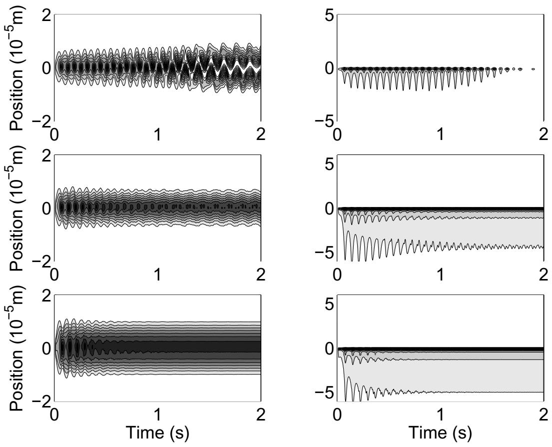

Figure 2: Pumped atom laser system with trapped (left) and untrapped fields (right). Interaction strength and stability increase downwards.

Control and stability of continuously pumped atom lasers: We have performed a comprehensive study of stability of a pumped atom laser in the presence of the pumping, damping and outcoupling. Previous work showed that a pumped atom laser is unstable in particular parameter regimes [1]. We developed a theory that shows how feedback can be used to remove energy from a fluctuating condensate [2]. The model demonstrated efficient BEC cooling by controlling only basic trap parameters.

We included this feedback scheme into our atom laser model. We find that extreme long term stability is still largely determined by the spatial dependence of the pumping mechanism, and the interatomic interaction energy. While the feedback scheme is highly efficient in reducing condensate fluctuations, it usually does not alter the stability class of a particular set of pumping, damping and outcoupling parameters. Feedback schemes will still be of great utility in experiments, as they dramatically improve the modal stability of the atom laser output over any finite temporal window.

References

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Matter-wave gap vortices in optical lattices

E. A. Ostrovskaya and Yu. S. Kivshar
ACQAO and Nonlinear Physics Centre,
Research School of Physical Sciences and Engineering, Australian National University, Australia

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 [1]. Within the framework of a continuous mean-field model we have shown that, in two-dimensional optical lattices, the nonlinear localization of BEC with repulsive atomic interactions is possible within a complete (finite) gap of the Bloch-wave spectrum [Fig. 1(top)]. The localized states forming near the bottom of the first finite gap (marked point in Fig. 1) take the form of bright atomic solitons [1] or vortices [2].

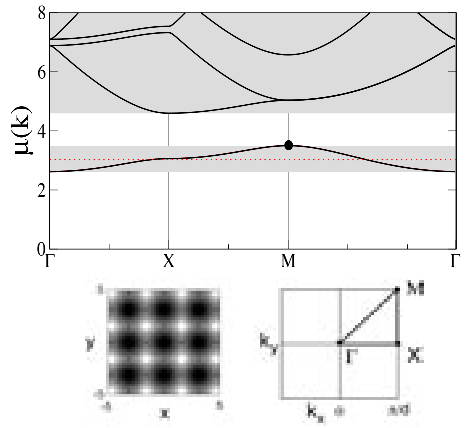

Figure 1: Matter-wave Bloch spectrum, $\mu(\mathbf{k})$ (where μ is the chemical potential), for the optical lattice potential $V(x,y) = V_0(\sin^2 x + \sin^2 y)$; $V_0 = 3E_{rec}$, where E_{rec} is the lattice recoil energy. Length unit is related to lattice spacing as d/π. The Bloch-wave bands are shaded. Below: Lattice potential and its first Brillouin zone.

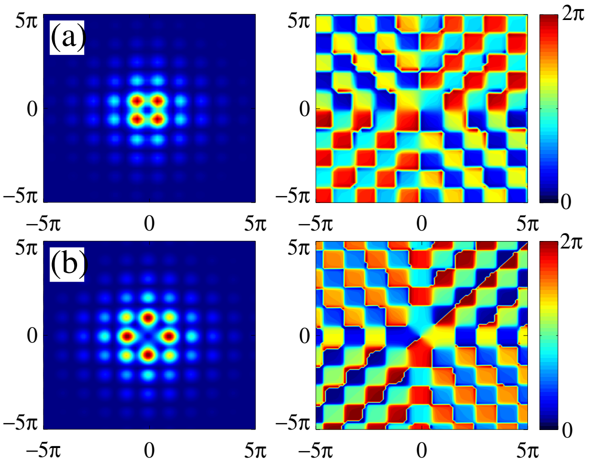

Figure 2: Condensate wavefunction $\psi(x,y)$ of the (a) off-site and (b) on-site cap vortex plotted together with the phase map ($\mu = 4.0$). Colorbar corresponds to the phase plots only.

Vortices can be supported by the lattice despite the non-conservation of angular momentum. 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. 2). 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. The lattice supports both close-range off-site gap vortices [Fig. 2 (a)] and long-range on-site vortices [Fig. 2 (b)] . Vortices that belong to either of these symmetry types can be dynamically stable.

Generation of localized vortices can, in principle, be achieved by adiabatically driving a broad BEC wavepacket to the edge of the first finite spectral gap (i.e. the extreme M edge of the first Brillouin zone). Subsequent imprinting of a $0 \to 2\pi$ phase ramp is also required. In dynamical simulations of the mean-field model, we have demonstrated that localization of vortices is a threshold effect, dependent on both the total number of atoms and the peak atomic density [2].

References

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Localization of two-component condensates in optical lattices

E. A. Ostrovskaya and Yu. S. Kivshar
ACQAO and Nonlinear Physics Centre,
Research School of Physical Sciences and Engineering, Australian National University, Australia

The existing experiments on Bose-Einstein condensates (BECs) in spin-dependent optical lattices [1], have demonstrated that the condensate components corresponding to two hyperfine states (e.g., $|a\rangle$ and $|b\rangle$) of the same atomic species can be coherently and, to a degree, independently, manipulated in the optical lattices. Inspired by these results, we have analyzed the nonlinear localization properties of a two-comonent condensate with repulsive atomic interactions in a one-dimensional lattice [2].

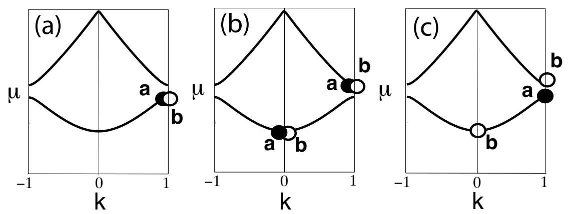

Figure 1: Schematics of the chemical potential vs quasimomentum of the BEC components $|a\rangle$ and $|b\rangle$ relative to the Bloch-wave spectrum. Nonlinear intra-component interactions are (a) attractive-attractive, (b) repulsive-repulsive, and (c) repulsive-attractive.

We found that it is possible to control the type and strength of nonlinear interactions both within and between the BEC components by exploiting the properties of the lattice band-gap structure, without Feshbach resonance manipulation of the scattering lengths. Three different regimes of the effective nonlinear interactions within and between condensate components can be realized for a two-component BEC in a lattice by appropriate preparation of the BEC wavepackets relative to the band structure of the Bloch matter-wave spectrum, as shown in Fig. 1.

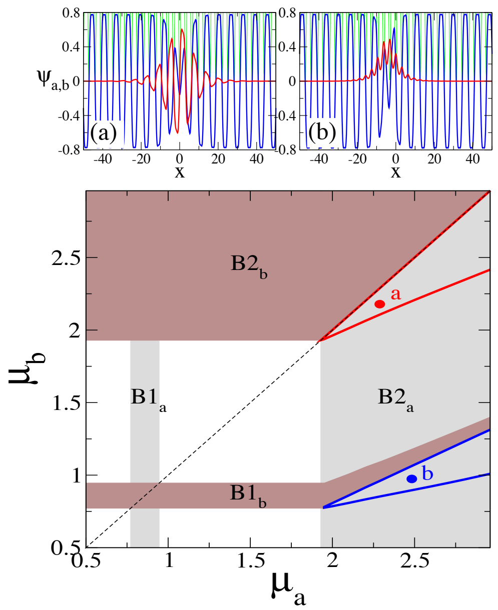

Figure 2: Solid lines: Existence domains for the dark-bright atomic solitons in the repulsive-repulsive interaction regime shown relative to the two lowest bands (shaded and marked B1 and B2) and gaps of the Bloch-wave spectrum for components $|a\rangle$ and $|b\rangle$. Top panels: Condensate wave functions at the marked points (a,b) of the composite soliton existence domains.

The most interesting consequence of this nonlinearity control is the formation of bright solitons in the repulsive BEC component, supported by an "effective" lattice imposed by the periodic Bloch state in the complementary condensate component. This can be achieved in the repulsive-repulsive interaction regime, e.g. when the component $|a\rangle$ is prepared at the edge of the second band [Fig. 1(b)]. Then it can support a dark soliton, phase-imprinted onto a Bloch-wave background. Moreover, due to the mean-field effect, the $|a\rangle$ component induces a periodic potential for the $|b\rangle$ component which acts together with the optical lattice potential. In the combined potential, the structure of the Bloch spectrum for the $|b\rangle$ component is significantly modified (Fig. 2). The $|b\rangle$ component can now be localized as a bright gap soliton in every gap of the induced band-gap structure. The existence domains for the coupled dark-bright states [Figs. 2 (a,b)] lie entirely within the original Bloch bands of the optical lattice. This type of localization could have a striking experimental signature whereby formation of a bright soliton in one of the BEC components can be achieved by phase imprinting onto the complementary component.

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Optimisation of spatial squeezing and measurements below the quantum noise limit

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Spatial measurements, such as the detection of the displacement and tilt of a beam of light, suffer from limitations in the accuracy similar to those encountered in temporal signals. The signal to noise ratio is limited by the quantum noise. However, it is possible to surpass this limit using spatial squeezing, in analogy to conventional temporal squeezing.

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. We 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. The challenge is to measure this information optimally. Furthermore, we found that a spatial homodyne detector that uses a TEM_{01} local oscillator, is ideally suited for these measurements. This scheme couples the TEM_{10} or TEM_{01} to the eigenmode of the detector. This results in a 20% increase in the efficiency of the conventional split detector.[3]

These ideas were turned into a real apparatus and 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 goals are to find more efficient ways of generating squeezed light in the TEM_{01} mode to demonstrate spatial entanglement and to look for practical applications of these new methods. In particular we have joined a team in Europe which proposes, as part of the EU six framework, to investigate enhanced techniques for optical data storage.

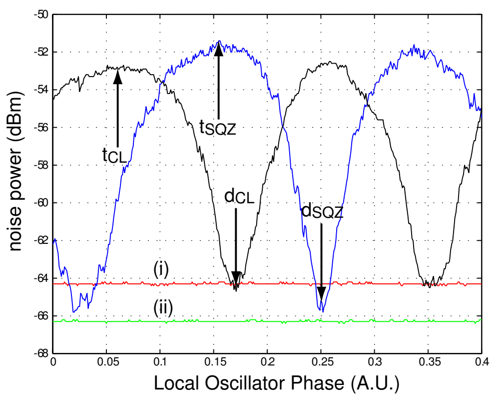

Figure 1: Spatial homodyne measurement with and without squeezing. The local oscillator has a TEM_{01} mode. The phase of the local oscillator is scanned, the measurement cycles from displacement (minimum) to tilt measurement (maximum). The classical measurement, without squeezing, are given by the quantum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

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Storing squeezing and entanglement in EIT systems

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The coherent and reversible storage of the quantum state of a light field is an important issue for the realization of many protocols in quantum information processing. In the past four years much work has been done on this topic utilizing the phenomenon of electromagnetically induced transparency (EIT). In the conventional EIT setup one makes use of an ensemble of Λ-level atoms, where the two lower levels are long-lived metastable states such that any coherence between them decays very slowly (on the order of milliseconds or longer). The ground states are coupled to the upper state by two electromagnetic fields: a strong coherent "control" field and a weak "probe" field. The control field is turned on first, and then a probe field pulse is sent into the medium. If the control field is now reduced to zero, the probe pulse is transferred to the atomic medium, its quantum information stored as an atomic coherence between the two ground states [1]. The probe pulse can then be regenerated by turning the control field back on at a later time, thus realizing the reversible storage of the quantum state of a light field.

Our interest was in extending previous work on this topic by quantifying the fidelity of such a scheme when one tries to store two specific forms of quantum information: squeezing and entanglement. In contrast to previous studies we took fully into account the effects of the ground state dephasing rate and the quantum noise contribution of the atoms. Our scheme is shown in Figure 1.

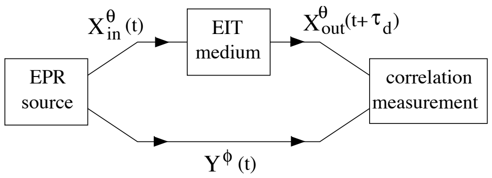

Figure 1: Schematic of a hypothetical quantum information delay experiment

$\hat{X}$ and $\hat{Y}$ are two entangled beams where $\hat{X}$ though the EIT medium and is consequently by a time τ_d while $\hat{Y}$ travels in a vacuum. The θ and ϕ denote the specific quadratures to be gated. To quantify entanglement we used Du seperability measure, and calculated the degrec entanglement and squeezing after passage thrc EIT medium. We determined that the degredatic quantum state can be made small (around 5%) istic parameter choices [2].

The atomic Λ-system has remarkably rich behaviour. Another aspect we investigated was an alternative to the usual retrieval scheme. We examined what happened if, after the quantum information has been stored in the atomic sample, we were to apply the retrieval control beam to the probe transition, rather than the original control beam transition. Remarkably, the probe pulse can still be regenerated, provided the relative atom-light coupling strengths for the two transitions are chosen appropriately. In this case the probe pulse is revived on the transition that was originally coupled by the control beam. We showed that this retrieved pulse is phase conjugated and time-reversed in shape [3]. In addition, with correctly chosen optical and atomic parameters, the system generates solitonic solutions that propagate through the medium. It should be noted, however, that the mechanism behind this retrieval is not a coherent process, and consequently this alternative scheme cannot be used for robust quantum information storage and retrieval, despite its other interesting features.

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Quantum Information

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The main focus of this area of research is the development of criteria for mesoscopic and macroscopic entanglement and their application to both continuous variable and discrete (spin) measurements on squeezed Gaussian states and macroscopic Bell states respectively. This involves several types of investigation. At the fundamental level, we are developing new EPR, Bell and GHZ related classical inequalities that are capable of extension to mesoscopic systems. In addition, we are calculating how quantum mechanics can violate these inequalities in practical experiments either in quantum optics or in atom optics, which can be carried out using known technologies.

A long-term objective is the extension of tests of quantum measurement theory to new regimes of large particle number. Ideally, we would like to have entangled massive particle states where different mass distributions are superimposed. This would allow for rigorous examination of proposed alternatives to quantum theory involving intrinsic or gravity-induced decoherence. A number of physical systems exist that can generate entangled states, and therefore part of the research is in the application of the criteria to realistic physical systems capable of being investigated experimentally in the ACQAO laboratories.

Work on constructing tests of the compatibility of mesoscopic and macroscopic superpositions with hidden variable theories that assume types of macroscopic reality has led to a paper by M. Reid being submitted to Phys. Rev. Lett. [1]. In response to comments from referees, a review of theoretical work behind the EPR-paradox and its relation to entanglement is being expanded to include analysis of experiments and will now involve collaboration with other authors and experimental groups. An investigation into triple-correlation inequalities applicable to continuous variable measurements is underway.

A study of the continuous variable EPR paradox in a travelling-wave second-harmonic generation system was published in Phys. Rev. A [2]. We have also investigated the use of coupled intracavity nonlinear waveguides operating in the down-conversion regime, focusing on quantum entanglement and the production of EPR states. This system can possibly be developed to give a monolithic apparatus for the production of continuous variable entanglement, which may provide improved stability compared to the existing ANU entanglement experiment.

While the EPR paradox is a first step towards demonstration of nonlocality, further investigations are needed to determine if this or a related system can be used to produce continuous variable violations of Bell's inequalities. As a first step in this direction, we have investigated the critical-point fluctuations of nondegenerate optical parametric oscillator (NDPO), and shown the existence of strongly non-classical triple correlations in the quadrature spectrum of this widely used device [3]. We have also calculated spatial effects at the critical point of a planar DPO, and are continuing work on correlations in cascaded NDPOs, which is immediately relevant to an experiment at Pfister's group in University of Virginia.

A paper on EPR correlations of massive particles is submitted to Phys. Rev. Lett. This is related to recent developments in coherent atom-molecular formation, and represents the first paper extending the new mesoscopic inequalities to massive particles. The details are available in the "Atomic-molecular BEC" project report. We will extend these investigations to fermion pairs, in view of the planned experimental developments at Swinburne University of Technology.

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Bose-Einstein Condensation on a Magnetic Film Atom Chip

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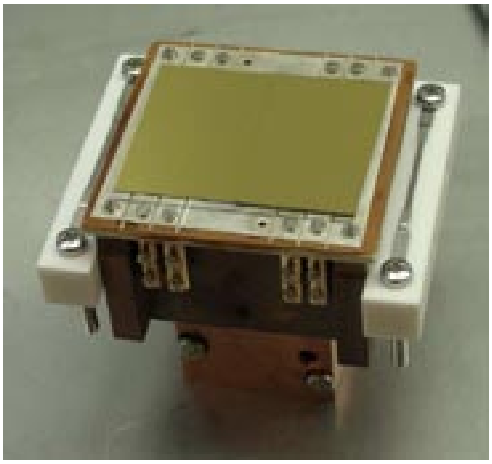
This project aims at the production of a Bose-Einstein condensate (BEC) of rubidium atoms on a permanent magnetic film atom chip [1] and the study of coherent and decoherent effects in single-atom and BEC-based atom interferometry. The Swinburne atom chip (see Figure) uses a unique two-layered structure consisting of a permanent magnetic film and current-carrying wires that allows us to combine the stability and reliability of permanent magnetic fields with the versatility of time-variable magnetic fields provided by the conductors. In 2004 we have produced an atom chip and studied different regimes of trapping and cooling of rubidium atoms down to quantum degeneracy. The bottom layer of the chip is made of 1 mm wide wires cut in a silver foil using a computer controlled milling machine. The milled pattern of the wires allows the creation of U-shaped (quadrupole trap), Z-shaped or H-shaped (Ioffe-Pritchard traps) magnetic microtraps. The top layer is formed by two glass slides coated with a gold film. One slide has a perpendicularly magnetised magnetic film (GdTbFeCo) with a thickness of 1 μm and will be used for the construction of a tightly confining permanent magnetic trap. We have developed the in-house technology for depositing multi-layer GdTbFeCo magnetic films with excellent magnetic and topological properties. Measurements of magnetic properties using a SQUID magnetometer and a Magneto-Optic Kerr effect apparatus give hysteresis loops with a shape close to rectangular. The magnetic films have high remanent magnetisation (3.8 kG), high coercivity (around 3 kOe) and excellent magnetic homogeneity.



The atom chip is installed in an ultra-high vacuum chamber and operates at a background pressure of around 10^{-11} Torr. During the loading stage the rubidium atoms are trapped in a reflection magneto-optical trap (MOT) from a vapour provided by a rubidium dispenser. The cold rubidium cloud containing around 5×10^8 atoms is positioned about 5 mm beneath the surface of the chip. During the next stage the atoms are transferred into a compressed MOT formed by a U-shaped current, the magnetic field gradient is increased to 60 G/cm and the cold cloud is moved to within 2 mm of the surface.

The trapping beams and the current through the wire are switched off and the atoms are optically pumped into the F = 2, m_F = +2 state. A current of 22 A through a Z-shaped wire is switched on and about 5×10^7 atoms are magnetically trapped in a microtrap located 1 mm beneath the surface. The current is ramped up to 28 A and the bias magnetic field is increased up to 55 G. The cold cloud is moved to within 450 μm from the surface and compressed in the trap with parameters ν_{rad} = 600 Hz and ν_{ax} = 20 Hz. The lifetime of the trapped atoms is 25 s and is affected by proximity to the surface. The atoms are evaporatively cooled in 10 s using an oscillating magnetic field with a logarithmic sweep of RF frequency in the range 15 - 0.75 MHz. Bi-modal distribution of atoms in time-of-flight expansion corresponding to the onset of BEC is observed with a final RF frequency of 765 kHz. A pure condensate of around 50,000 atoms appears with a final RF frequency of 755 kHz.

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Progress 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 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. The systems initially chosen for study were molecular gases obtained from bosonic atoms (^{87}Rb, ^{133}Cs). However, investigations during the last 12 months 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 April 2004, a decision was made by our MBEC group to switch from ^{133}Cs to ^{6}Li. The above objectives will be investigated in the context of a MBEC obtained from fermionic ^{6}Li atoms. In our experimental scheme a $\sigma-$ Zeeman slower will be used to produce a continuous high-flux beam of ^{6}Li atoms at speeds low enough to load a magneto-optical trap (MOT). The atoms are then transferred to a far-off-resonant optical dipole trap (FORT), which is used to trap and evaporate the atoms and molecules. The scattering length of the atoms will be controlled via Feshbach resonances in magnetic fields up to 1.5 kG. 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].

The initial setting up of the experimental apparatus is nearing completion. The UHV system for the lithium beam line has been designed, and is presently being constructed, including a custom glass cell for producing the MBEC. A Zeeman slower has been designed and built and is currently being tested. Feshbach coils, capable of producing magnetic fields up to 1.5 kG, have been assembled. A Toptica DL100 15 mW tunable extended-cavity diode laser has recently arrived, and has been frequency locked to the 671 nm ^{6}Li resonance using a specially constructed high-temperature ^{6}Li vapour cell. Several laser diodes have been evaluated and successfully injection-locked to the master laser (Toptica). A 20 W single-frequency ELS Yb:YAG laser at 1030 nm, which is to be used for the FORT trap, has been purchased and delivered. Switching electronics for controlling the Feshbach and MOT coils have been designed and constructed.

Theoretical research on processes for generating molecular BECs from atomic condensates is being carried out. One process of interest combines a Feshbach resonance with STIRAP (Stimulated Raman Adiabatic Passage) leading to a molecular condensate in the ground vibrational state, and hence closer to absolute zero in temperature. Ideally, such conversion processes are coherent, but various decoherence processes such as spontaneous emission need to be taken into account to be realistic. Also, quantum fluctuations around the condensate wavefunctions, occurring when the number of atoms or molecules is small, would be important. The unified quantum Monte Carlo formalism developed by the University of Queensland group in ACQAO [5] could be suitable for treating these issues, though a multi-component version to allow for both fermionic atoms and bosonic molecular condensates would be required.

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Atomic-molecular Bose-Einstein condensates

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Coupled atomic-molecular BECs, together with the studies of BCS-BEC crossover in degenerate Fermi gases, are currently one of the most active research topics in the field of ultracold quantum gases. In this ACQAO project, we have made progress on several fronts:

1. We have completed [1] an investigation of several recent reports of Feshbach resonance experiments, and shown that, after renormalization of the interactions, the experimental results agree well with our analytic predictions of the dressed-molecule binding energies. This verifies our original model introduced in 1998. The calculation of binding energies now includes molecular dimers consisting of fermionic atoms (^{6}Li and ^{40}K), in addition to the earlier studied case of bosonic ^{85}Rb atoms.

2. We have completed work on three-dimensional (3D) soliton formation in coupled atomic-molecular BECs [2]. The work is mostly numerical, using mean-field techniques, and indicates stable localized solitons of atoms and molecules in 3D, which cannot exist in a normal single-component BEC.

3. We have submitted a Reply to "Comment on 'Stimulated Raman adiabatic passage from an atomic to a molecular Bose-Einstein condensate'" [3]. This paper discusses optimization issues in STIRAP and is to appear in Phys. Rev. A. We have also studied the role of the initial quantum statistics of the atomic BEC on the efficiency of conversion into a molecular BEC via photo-association [4].

4. We have studied [5] a scheme for matter-wave parametric amplification and phase-conjugation of an atomic BEC via stimulated dissociation of a BEC of molecular dimers consisting of bosonic atoms. We have shown that the interaction of a small incoming atomic BEC with a (stationary) molecular BEC can produce two counterpropagating atomic beams – an amplified atomic BEC and its phase-conjugate or "time-reversed" replica. The two beams can possess strong quantum correlation in the relative particle number, with squeezed number-difference fluctuations.

5. 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 output 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.

6. We have started a program on ultracold Fermi gases to support the Swinburne planned ^{6}Li experiment. A paper on unified Fermi/Bose representations and Gaussian quantum Monte-Carlo methods for fermions has been published in Phys. Rev. Lett. (see "Representation theory" project).

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Theory of Double-Well Atom Interferometry

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Novel theoretical treatments are being developed for double-well atom interferometers (DWAI) that are based on the splitting of a single-well potential into two wells, non-adiabatic phase evolution of quantum states due to an applied spatially-asymmetric potential and then recombination into the original potential well. The non-adiabatic stage involves transitions between the nearly degenerate ground and first excited vibrational states of the confining potential, and the probability of finding the atom in the excited state provides a measure of the effect of the spatially-asymmetric potential. Such an atom interferometer can be considered as a Mach-Zehnder interferometer, where the quantum states localised in two separate wells represent different optical paths. DWAI for both the single-atom and BEC cases are well suited to implementation on atom chips [1], where micron scale dimensions of atom optical elements allow precise control over the splitting and recombining processes.

For a single-atom DWAI our approach [2] takes account of the presence of asymmetry during the splitting and recombination stages. The theory is based on a two-mode approximation and leads to a Bloch vector model. The formal similarity of the atom interferometer system to a driven two-level atom enables us to introduce atomic spin operators and to write the dynamical equations as Bloch equations. This approach allows the use of the Bloch sphere for a clear interpretation of the dynamical processes. For certain conditions we obtain an analytical solution describing the interferometric process. The outcomes of the Bloch vector model are compared with the results of numerical simulations of splitting and recombination carried out by solving the time-dependent Schrödinger equation using the XMDS (eXtensible Multi-Dimensional Simulations) software package developed by the theory group at the University of Queensland. By studying time-dependent splitting processes we are able to optimise the sensitivity of the interferometer and its tolerance to external perturbations.

As an extension of the single-atom case to a multiple-particle Bose-Einstein condensate (BEC) situation, a theory of double-well interferometry has been developed using the two-mode approximation for small atom numbers, where the mean field energy term is much less than the vibrational energy quantum for the trap. This results in self-consistent equations coupling the two condensate wave functions and the amplitudes of Fock states describing possible fragmented condensates [3]. In a Bloch sphere variant of the theory, the BEC behaves as a giant spin system.

A more general theoretical treatment of DWAI using BEC is also being developed using the stochastic gauge theory approach [4] 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 [5], relating the fidelity loss to the quantum state and to Markovian relaxation rates. The approach could be applied to study decoherence effects in DWAI using BECs.

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Low dimensional quantum gases

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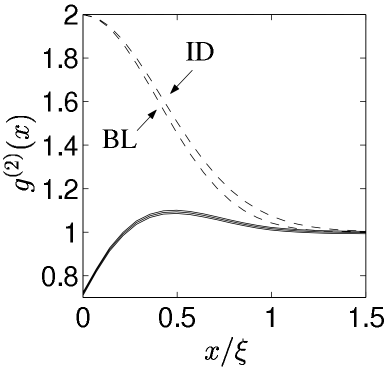
Low-dimensional quantum gases are examples of strongly correlated quantum systems – the subject of intense theoretical and experimental activity in many areas of physics. These studies have relevance to the ACQAO experimental program in the areas of atom chips and optical lattices, as well as to possible future atom-counting experiments. Recently, there has been a major experimental breakthrough: several laboratories have reported demonstration of the famous Tonks-Girardeau regime of a 1D Bose gas in which strongly correlated bosonic atoms acquire "fermionic" properties. Models of 1D quantum gases have the important property that their energy eigenstates are exactly solvable, but more general techniques are needed to calculate other properties.

We have developed and carried out canonical Bose gas simulations using a novel stochastic gauge technique, and calculated the non-local pair correlation for a uniform 1D Bose gas with delta-function interactions between the particles [1, 2]. This work is generically applicable to any quantum gas at finite temperatures, even in cases where exact analytical approaches do not exist.



The figure on the left is an example of the non-local second-order spatial correlation function

$$g^{(2)}(x) = \frac{\langle \hat{\Psi}^\dagger(0)\hat{\Psi}^\dagger(x)\hat{\Psi}(x)\hat{\Psi}(0)\rangle}{\langle \hat{\Psi}^\dagger(0)\hat{\Psi}(0)\rangle\langle \hat{\Psi}^\dagger(x)\hat{\Psi}(x)\rangle} \tag{1}$$

for $\gamma = T_{rel} = 10$. The solid line is the result of numerical simulations, while the dashed lines are the results for $\gamma = 0$ ideal Bose gas (ID) and a high-temperature ($T_{rel} \to \infty$) Boltzmann (BL) gas. The spatial correlation exhibits a highly nontrivial structure, with the peak at $x \simeq 0.5\,\xi$ showing the most likely separation between the particles.

The results at $x = 0$, showing anti-bunching ($g^{(2)}(0) < 1$), are in excellent agreement with our exact calculation of the local pair correlation in 2003, which was recently confirmed experimentally by the group of W. Phillips [B. L. Tolra *et al.*, Phys. Rev. Lett. **92**, 190401 (2004)].

We have extended our studies of local pair correlations to non-uniform (harmonically trapped) 1D Bose gases, which are more relevant to practice. General hydrodynamic equations have been derived, and results are in good agreement with the latest dynamical expansion experiments of D. Weiss's group at Penn. State. An investigation into discrete vortices and vortex loops in a novel tetrahedral optical lattice structure is also underway, together with the ANU theory group of Yu. Kivshar *et al*.

Finally, 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, using the Luttinger liquid theory. We predict a strong quenching of the collective modes at the transition point, with details included in the Ultra-cold Fermi gas report.

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Ultra-cold Fermi gases

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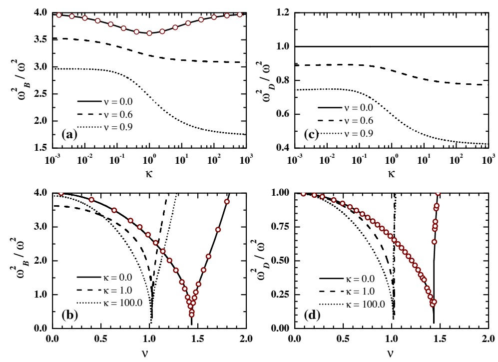
Recent experiments with ultra-cold fermionic atomic gases are rapidly developing into a research field as significant as Bose-Einstein condensation. Accordingly, we have commenced a wide-ranging theoretical program to investigate new physics in these systems. As a starting point, we are investigating the observable signatures of the Mott metal-insulator transition (MMIT), which is fundamental to strongly correlated many-body systems.

The MMIT with bosonic atoms has been demonstrated by Greiner *et al.* [1]. A demonstration with fermions has not yet been realized experimentally, although its realization is within reach of present-day techniques. In the fermionic case, the relevant theory is the widely studied Hubbard model. This is the simplest lattice model of interacting fermions, and is exactly soluble in one dimension. An interacting gas of ultra-cold fermions with two populated hyperfine levels in a one-dimensional lattice is also feasible, thus offering the possibility of observing the fermionic MMIT.

Motivated by this opportunity, we address the problem of how to detect the emergence of fermionic Mott-insulator phases in real experiments with ultra-cold fermions. 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 Bethe ansatz solution of the homogeneous 1D Hubbard model [2], together with the local density approximation (LDA), 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 (LL) theory [3], which describes long wavelength hydrodynamic behaviour.



The figure on the left gives the square of frequencies of the breathing mode and of the dipole mode at fixed values of ν and of κ. We find that in the metallic phase the collective oscillation is an overall motion that goes through all sites of the cloud. This quenches gradually towards the phase transition point, with the mode frequency decreasing monotonically to zero. After entering the Mott-insulator phase, the density oscillation revives, but is restricted to the compressible wings.

In summary, we predict a sharp dip in all collective mode frequencies in the vicinity of the phase boundary, giving a clear signature of the MMIT[4].

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Representation theory

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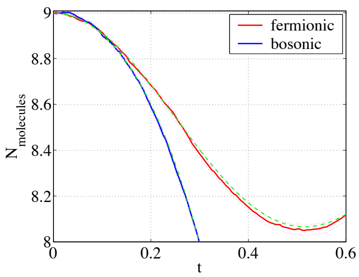
The physics of quantum, many-body systems underlies the whole ACQAO research program, and tractable methods to simulate this physics is the goal of the research stream in quantum phase-space methods. The methods are based on techniques that were originally developed in quantum optics and are now being tailored to systems of massive particles, i.e., electrons, atoms or molecules.

The main thrust of this program is to radically improve the efficiency and applicability of phase-space methods through new *operator* bases. The choice of basis determines the basic structure of the method and its suitability to different physical situations. A basic motivation is to include in the basis itself states which are a closer match to the physical density matrix of the system being studied, leading to greater efficiency in the stochastic sampling. Optimizing the operator basis is a much more general and powerful procedure than modifying the quantum state basis.

The methods used here generalize the non-classical positive-P representation. We have shown that these new techniques are able to deal with extremely complex irreversible master equations [1, 2] and even time-reversible quantum dynamical behaviour in an interacting 10^{23} particle system [3]. In 2003, we developed the Gaussian representation for bosons, which incorporated and extended the coherent-state based methods from quantum optics. More recent work exploited the fact that the Gaussian expansion can naturally be adapted to treat *fermionic* systems. In either fermionic or bosonic cases, the expansion is useful both in real time and as a technique for calculating correlations at finite temperature.



The figure on the left is an example of quantum dynamical calculations using the new phase-space representations. It illustrates the physics of Pauli blocking in the downconversion of a bosonic molecular BEC to atoms, in a one-mode trap inside an optical lattice. In the case of fermionic atoms, the downconversion can only produce a single pair of atoms per mode, resulting in a Rabi-cycling from molecules to atoms and back.

Having developed the formalism of the fermionic Gaussian method, we have concentrated on applying it to the Hubbard model, an important system in condensed matter physics and one that also describes an ultracold Fermi gas in a optical lattice. We have successfully simulated the finite-temperature Hubbard model for up to a 16x16 2D lattice and 6x6x6 3D lattice, in cases where there is a significant sign problem with traditional quantum Monte-Carlo methods (QMC). We have incorporated a genetic branching algorithm (from Green's function QMC), in order to reduce the sampling error.

In a paper recently published in Physical Review Letters [4], we introduce the fermionic Gaussian representation and present the first simulation results using the Gaussian method for Bose and Fermi systems. In particular, this paper includes spectacularly well-converged Hubbard results. This shows that we been able to overcome the long-standing Fermi sign problem for this system.

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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. 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.

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.

The central speed of the ring vortex component may be reduced by changing the symmetry of the trap to cylindrical, with the long axis parallel to the line vortex singularity. This is because the circulation is fixed at one quantised unit, so as the length increases the speed decreases. This enables us to reduce the number of atoms to around one million while remaining stable against shrinking of the ring vortex.

To stabilise these low atom number skyrmions against drift of the line vortex out of the trap we found that both rotation and laser pinning were required.

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.

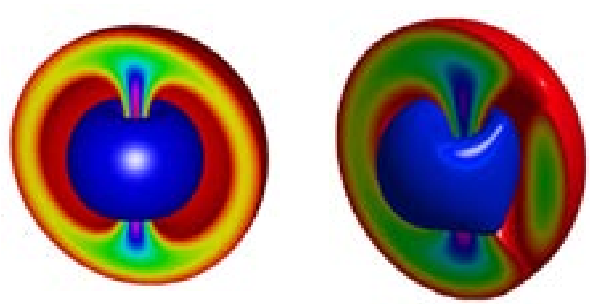

Figure: (Left) 3D density profile of a trapped skyrmion. The central torus is an isosurface of the atomic state forming a line vortex. The other atomic state forms a ring vortex: isosurfaces are shown for $x < 0$. On the $y - z$ plane between the isosurface sections, density is indicated by a colormap.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

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Collapsing BECs beyond the Gross-Pitaevskii approximation

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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.

The classical field techniques being developed at the University of Queensland also lend themselves to quantum simulations of Bose degenerate gases. Trajectories in the truncated Wigner phase space method obey the GP equation but with additional noise to take quantum effects into account. Preliminary Wigner calculations, that have been performed to determine the influence of quantum and/or thermal noise, agree with the HFB results.

Further work might employ a different factorisation scheme for the correlation functions, for example the method of non-commutative cumulants put forward in [5], which differs from ours in its truncation method. To determine the rate of spontaneous production of uncondensed atoms in that formalism we would need to include the higher order correlation functions in our simulations.

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Detecting atomic fields

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Limits to optical detection: Many experiments on ultra-cold atoms require detection of atomic density that is not only sensitive, but also non-destructive. A major difficulty is that a single photon recoil has the energy of over a thousand atoms in a typical Bose-Einstein condensate, so spontaneous emission is an extremely destructive process. All optical techniques used to probe the properties of atoms have been based on absorption or dispersion, both of which we have shown previously to have a lower limit to the maximum possible signal to noise ratio (SNR) for a given spontaneous emission rate [1, 2]. This result is obvious for an absorptive measurement, but for a phase-based measurement it relies on a limit on the phase shift imparted on a light beam for a given excited state population of the atoms. The only loopholes in these earlier results are to use multi-level atomic schemes, non-coherent light, or to multi-pass the light through the atomic sample.

The fact that in three-level systems with a strong driving field, a probe field can experience finite phase shift with no absorption suggests that multi-level schemes may provide a superior measurement of the atomic density without increasing the spontaneous emission rate. The lack of absorption is characterised by a zero in the imaginary part of the susceptibility, which does not automatically correspond to a zero excited state population or zero spontaneous emission rate. Using the relationship between the susceptibility of a three-level medium and the off-diagonal density matrix elements of the atomic system, we deduced an inequality that lead to a bound limiting the maximum phase shift possible for a three-level system with a given excited state population. This limit was identical in form to the two-level case when a different laser addressed each field of the Raman transition, and it was a trivial generalisation of that form when a single laser coupled both transitions. The result was that we demonstrated that a trivial generalisation of the non-destructive detection limit for the two level atoms applied to three-level schemes [3].

The treatment applied to the three-level system is trivially generalised to any number of levels and lasers providing the response of the medium to the optical fields can be described in terms of linear susceptibilities. By identifying the origin of the phase shift on the lasers as the eigenvalue shifts of the dressed state energy levels, we managed to calculate the phase shift of a light beam in a non-linear system consisting of any number of laser fields coupling to any number of atomic transitions. This showed that the limit derived in the linear response regime is in fact general to any detection scheme [4]. The only way to improve a non-destructive, optical measurement beyond the limit imposed by the theorem is to use multi-pass interferometry, or to use non-classical light fields such as a squeezed field. Both of these approaches have significant technical challenges.

Detection of atomic quadratures: Of all possible observables, density is by far the easiest to measure for atomic fields. This is the same with optical fields, but atomic fields suffer from the lack of a suitable phase reference like the local oscillator in optical experiments. This makes it essentially impossible to make a phase-sensitive measurement, such as a quadrature measurement. The free space dispersion of the atomic field simplifies the technique of self-homodyne tomography, however, where quadrature correlations between frequency components on either side of a coherent central frequency can be measured without a separate local oscillator field. Arbitrary quadrature correlations can be reconstructed by simply moving the detector, or introducing a controllable potential in the path of the atomic beam.

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Piezo-locking a Diode Laser with Saturated Absorption Spectroscopy

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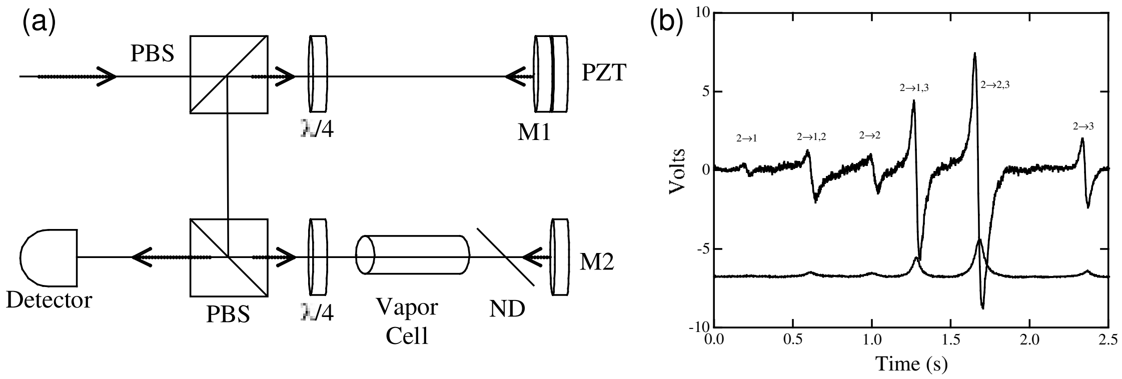
Saturated absorption spectroscopy is a ubiquitous method of frequency stabilizing diode lasers in many areas of atomic physics such as: spectroscopy, atomic clocks, laser cooling and Bose-Einstein condensation. Several methods for obtaining an error signal from an atomic transition are currently in use [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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Superradiant scattering from a hydrodynamic vortex

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We showed 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]. However a sonic horizon analogous to the black hole event horizon does not exist unless the vortex possesses a central drain, which is challenging to produce experimentally. In astrophysics, superradiance can occur even in the absence of an event horizon: we showed that in the hydrodynamic analogue, a drain is not required and a vortex scatters sound superradiantly. We considered possible experimental realization in dilute gas Bose-Einstein condensates.

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

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

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

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

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 $\omega < m\alpha/r_0^2$.

Experiments on phonon superradiance in dilute gas Bose-Einstein condensates might provide a useful step towards the ultimate goal of observing the sonic analogue of Hawking radiation.

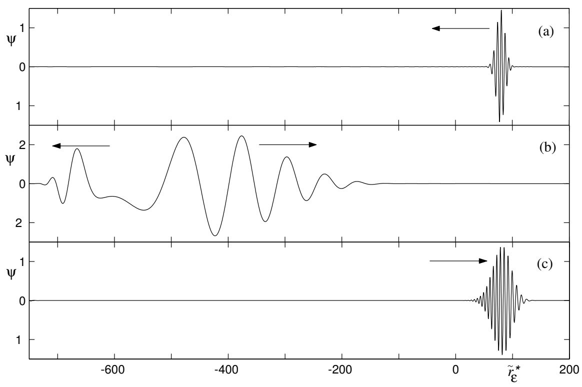

Figure. Wavepacket propagation from numerical solution of the wave equation. The real part of the wave packet is plotted versus the dimensionless modified radial tortoise coordinate $\tilde{r}^*_\epsilon$, defined in reference [1]. (a) the wavepacket is propagating towards the vortex. (b) the wavepacket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

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Mobility and interaction of matter-wave solitons in optical lattices

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Localization of matter waves in optical lattices is possible due to the balance of nonlinearity and dispersion which is modified by the band-gap spectrum of matter waves in a periodic potential. Nonlinear localization of a Bose-Einstein condensate with repulsive interatomic interactions loaded into a one-dimensional (1D) optical lattice can occur in the form of both bright and dark solitons. Dark solitons can form within the bands, and bright solitons within the gaps of the Bloch-wave band-gap spectrum.

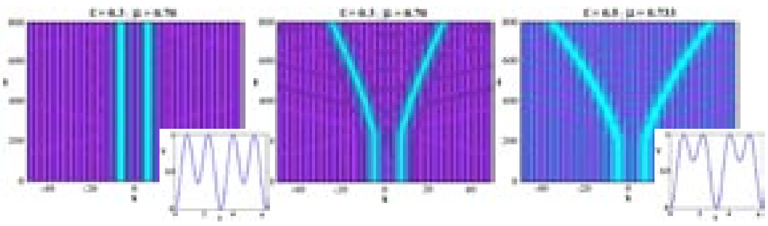

Figure 1: Controlling dark soliton interactions in an optical superlattice by changing the superlattice parameter, ε. Shown is dynamics of solitons centered on large (left) or small (middle, right) wells of the superlattice potentials displayed on the insets. The limits $\varepsilon \to 0, 1$ correspond to single-periodic lattices; $t = 800$ - to 13.6 ms [1].

We have investigated the existence and mobility of dark solitons in a shallow 1D lattice [1], and found that their mobility is well described by the concept of the effective Peierls Nabarro (PN) potential barrier, borrowed from the theory of discrete systems. We have demonstrated that fine-tuning of the PN barrier in double-period optical superlattices can enable effective control of interaction properties of dark solitons (see Fig. 1). Dark lattice solitons are especially interesting from the experimental point of view since they could be created by phase-imprinting onto spatially extended Bloch states of the condensate. In contrast, bright solitons can only be created in the gap, and currently only the near-band-edge region of the gap is accessible experimentally [2].

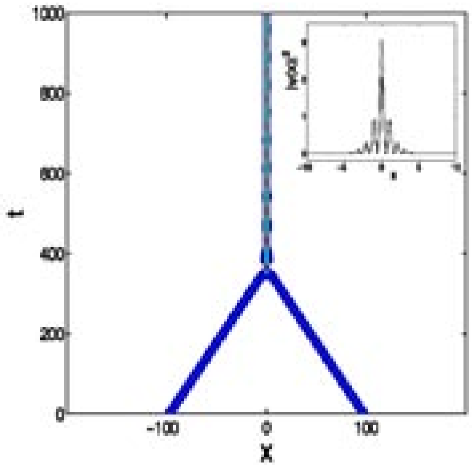

Figure 2: Fusion of two gap solitons into a new gap soliton. The initial (not shown) and final state (inset) contain 170 and 270 atoms, respectively [3].

The matter-wave gap solitons near the edge of the spectral band contain small number of atoms and are weakly localized. In order to improve localization properties, an access to the depth of the gap is needed. At the same time, near-band-edge solitons have good mobility due to low values of the effective Peierls-Nabarro potential barrier that inhibits mobility of localized states in periodic systems. In our work on mobility and interaction properties of gap solitons in a 1D lattice [3], we have shown that the excellent mobility of gap solitons enables the study of collisions of two (and more) near-edge gap solitons. The inelastic collisions and soliton fusion, arising in the certain domain of chemical potential and velocity values, could be employed to generate localized states with the chemical potential deep inside the spectral gap (see Fig. 2).

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Dynamical simulations of thermal Bose-Einstein condensates

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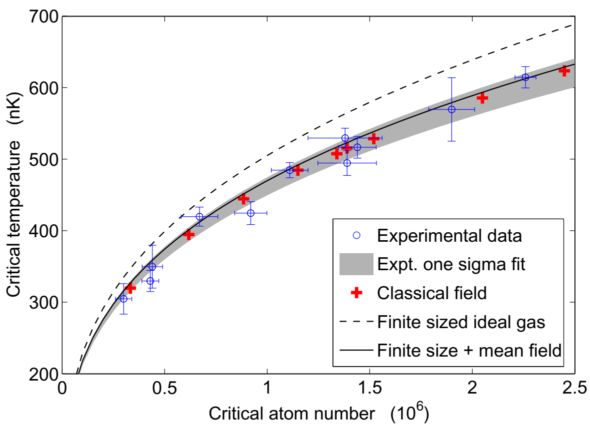
The increasingly common "classical field approximation" uses the Gross-Pitaevskii equation (GPE) as a model of Bose-Einstein condensates at finite temperature, in much the same way as the highly occupied modes of the electromagnetic field can be treated classically. An essential part of the method is that there is a well-defined mode cutoff, so that only the highly-occupied modes are represented by the GPE. The eventual goal is the quantitative implementation of a computational method to simulate BECs in the presence of a significant thermal fraction. While necessarily being an approximate scheme, it is aimed at performing calculations for realistic experimental systems.

The method has continued to be developed for harmonically trapped systems, rather than for the somewhat idealised case of the homogeneous gas [1]. This is done by carrying out simulations using an efficient quadrature for the harmonic oscillator basis rather than on a computational grid. The Penrose-Onsager condition for BEC has been investigated for these systems, and we have found that to a good approximation condensate fractions can be determined by fitting bimodal distributions to single time momentum space density profiles, in a similar manner to experimental procedures. We have also calculated spatial correlation functions and observed the transition from coherent to thermal fluctuations further from trap centre. These results have recently been submitted for publication [2]. This method can also address the issue of critical fluctuations and the shift in the critical temperature in trapped Bose gases, a nontrivial calculation. The figure displays the results of a comparison of this theory with a perturbative calculation and the experimental results of Gerbier *et al.* [3].



A topic of interest has been the reliability of the classical field simulations as GPE is chaotic. We have investigated the parameter regime for reversibility of the simulations in the homogeneous case, as well as the role of cumulative numerical errors. More recently attention has been given to the pairing of vortices and the Kosterlitz-Thouless transition in 2D system. This research is being carried out with the goal of investigating the formation of topological defects in the phase transition, using the formalism of the stochastic GPE as described in Ref. [4].

A related project is the kinetic theory of the continuous-wave atom laser. This takes the quantum kinetic theory formalism that has proved mostly successful for the problem of the dynamics of condensate formation, and adds in the prospect of replenishing the thermal cloud while performing evaporative cooling and simultaneously extracting an atom laser beam. It has been necessary to incorporate a full description of three-body loss into this calculation, and with this an investigation of the physical requirements for operating a cw atom laser is being carried out.

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Progress Towards Bose Einstein Condensation of Metastable Helium

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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 BEC's 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. 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 [1] predict that the "build-up" of relative phase should be seen after a measurement of only $\sim$ 50 atoms, making such an experiment extremely difficult with alkali BEC's for which efficient single atom detection is virtually impossible.

Much progress has been made this year towards our goal of creating a He* BEC. Early in the year we transferred the experimental rig into a new purpose built laboratory. After minimal down time, we were able to use the state-of-the-art metastable helium beamline, built last year, to load in excess of 3x10^9 atoms into a magneto-optic trap (MOT). This is the largest number of trapped He* atoms ever reported and forms an ideal source of atoms for a low velocity intense beam of He*.

Our major achievement this year has been demonstrating a low velocity intense beam of He*. By placing a dark spot in one of the MOT laser beams, radiation pressure imbalances force the atoms out of the MOT and into a well collimated beam [2]. This beam is intense, up to 7x10^9 atoms/s, with a most probable velocity $\sim$ 35 m/s and a divergence of $\sim$ 75 mRad. Using this atomic beam to load atoms into a second MOT, locatedin a region of ultra high vacuum, considerably simplifies the design of our magnetic trap. This is because the low divergence of the atomic beam allows the magnetic trap coils to be placed $\sim$ 1 cm apart, minimising the amount of amp-turns required to generate the large magnetic field gradients required for magnetic trapping.

In the coming year we plan to use the low velocity intense beam to load a magnetic trap and subsequent radio frequency evaporation should lead to condensation of He*.

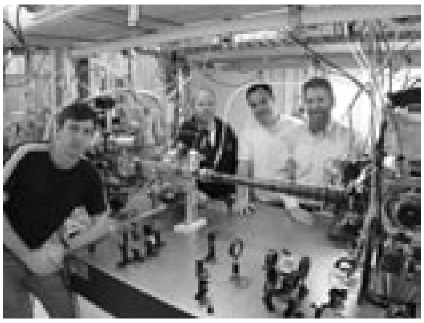

Figure 1: The helium BEC team, from left to right, Robert Dall, Steven Battisson, Andrew Truscott and Ken Baldwin. Also shown in the picture is the helium beamline, located in the newly built laboratory.

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ASSETS

Kioloa Workshop participants

The biggest asset for our research is people. We have an excellent group of people and are giving them improved opportunities for research through reduced teaching loads, improved laboratories and offices as well as the opportunity to travel within ACQAO and throughout the world. Many are fully funded by the Centre. 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.

A small and effective administrative team, (Ruth Wilson COO, Max Colla at ANU, Sharon Jesson at SUT, Diane Hutton at UQ, Wendy Quinn at IAS) has taken over the financial and organisational work, creating more time for research.

We have been able to attract excellent additional staff. In 2004 Murray Olsen and Xia-Ji Liu have joined UQ, Brenton Hall and Grainne Duffy at SUT with Tristram Alexander, Chaohong Li, Cristina Figl, Charles Harb and Mattias Johnsson, joining the ANU. We are particularly proud that we were able to bring Australians who work overseas back to Australia (Brenton Hall from the UK to SUT and Charles Harb from the US to 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 and students is given on page 42.

The other big asset is our research laboratories. We started with excellent facilities at SUT and ANU. We have built a new, custom made laboratory for the He* BEC project in the ANU IAS Node and have a new large laboratory at the ANU Faculties.

All of our experiments have gained significantly from a wide range of new equipment, which makes our work competitive on the global stage. The large equipment funding within our Centre budget has allowed us to build our experiments as quickly as possible, on timescales comparable to that of overseas research Centres.

The ACQAO team at Coolum Workshop

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 where a cotutelle (joint PhD project) is operating successfully (V. Delaubert), and staff have been exchanged (N. Treps, H-A. Bachor, L. Longcharbon) and have visited us (G. Shlyapnikov)
- Hannover with BEC on a chip where a joint PhD program (F. Scharnberg) continues and we exchange students.
- Amsterdam where we continue to exchange technical expertise and they have just achieved a metastable helium BEC.
- London with BEC on a chip where we gain expertise through a Research Fellow (B.Hall joined SUT)
- Dunedin where we have started joint projects (R. Ballagh, M. Davis).

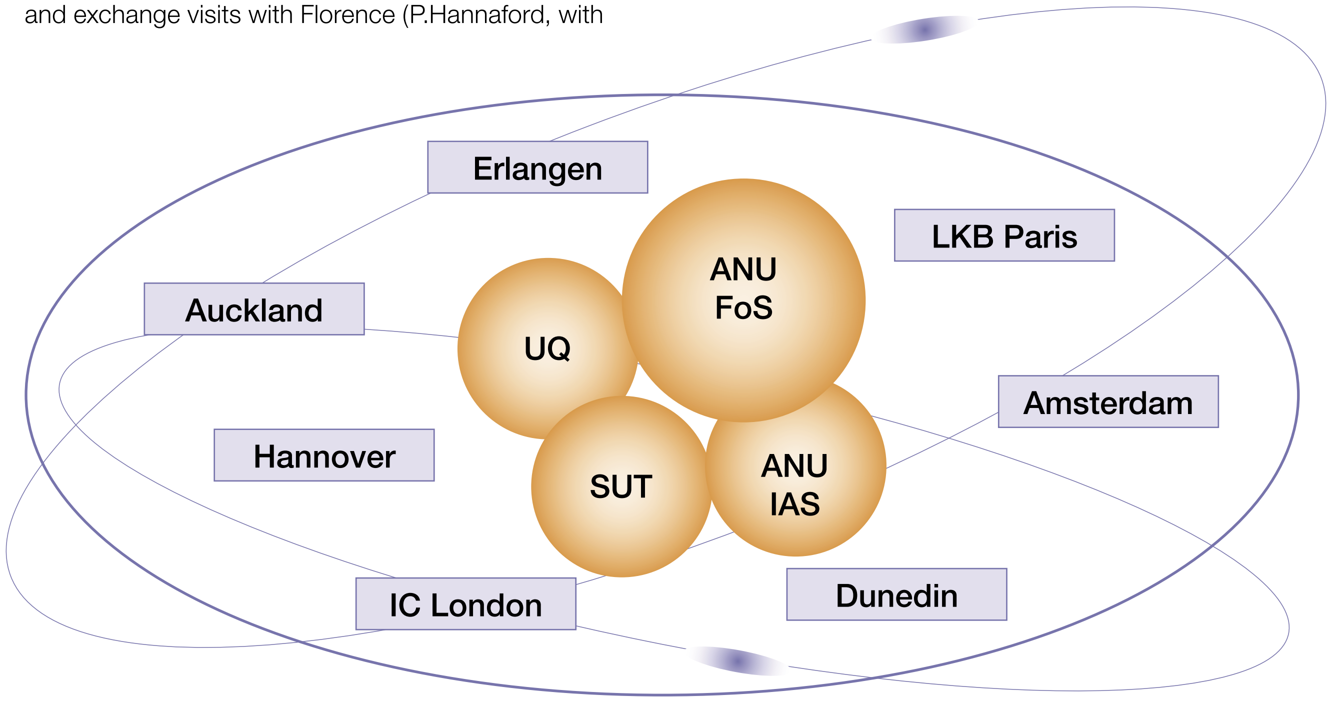
In addition we have expanded working relationships and exchange visits with Florence (P.Hannaford, with J. Lye joining LENS), and the University of Innsbruck (R. Blatt, R. Grimm, A. Sidorov, G. Duffy, H-A. Bachor). This brings expertise to Australia, enhances our international profile and in several cases has led to joint publications listed on page 30.

ACQAO has participated in a proposal for funding in a European research networks (on quantum imaging).

We have signed a contract with the Sonderforschungsbereich in Hannover and the CNRS in Orsay to organise annual quantum workshops over three years — the first one was held in Hannover in March 2004, the second one is in Les Houches, France February 2005 and the third in Australia in February 2006.

In 2003 we held the International Conference of Laser Spectroscopy (ICOLS) in Cairns, with the organizing team led by P.Hannaford, all from ACQAO. This was a spectacular success that brought more than 150 scientists representing the leading research groups to Australia.

In December 2004 we held the National Quantum-Atom Optics Summer School in Canberra which attracted 60 of the best Honours and potential PhD students to be inspired by talks given by some of the international leaders in our field, including Bill Phillips, Alain Aspect, Alan Griffin, and Keith Burnett.



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

In addition, in December 2004 the ANU Node hosted a workshop at Kioloa with 95 participants from around the country and including 12 international visitors which produced excellent discussions.

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.

Participants at the 2004 Australian & International Workshop on Quantum & Atom Optics

Commercialisation

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

In 2003 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 two project where we are supporting the development of a new, economical technique for locking the frequency of a tuneable laser to an atomic transition. John Close and Nick Robins have applied for a provisional patent for such device. The second project is being carried out by Ken Baldwin and Andrew Truscott who will develop a practical instrument for the measurement of the phase of coherent atoms.

In addition, the UQ group is further developing the software code XMDS which could be licensed commercially in the future.

Outreach

Outreach is an important mission of the Centre — we intend 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 Australian Science Olympiads and Questacon. Staff at ANU contributed to all these programs and reached more than 800 students and 30 teachers.

We organised public lectures by Prof D.Pritchard (MIT) in Canberra, Melbourne and Brisbane on *BEC the coldest place on earth* and Prof A.Aspect (Institut d'Optique) on *History and future of entanglement*. These enthusiastic and engaging lectures drew capacity crowds at the ANU and at the National Science and Technology Centre and made our research accessible to a very wide audience.

In addition to our international journal and conference publications, the publication of the proceedings of the ICOLS conference has helped disseminate our latest scientific results to an international audience.

Ruth Wilson, our COO, has started an active PR program with material sent to the media during the year and coverage gained as detailed on page 37–39.

As part of its commitment to Australian optics, ACQAO is a corporate member of the Australian Optical Society.

ACQAO also decided to sponsor two keynote speakers at the AIP Congress in Canberra for February 2005.

Prof William Phillips talks with Mandip Singh, Saeed Ghanbari and Mile Gu at the ACQAO Summer School

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.

The Centre gave us the opportunity to start several ambitious programs and some of them — particularly those involving the construction of complex experimental facilities — will require two years before we have the first results. At the same time we are already producing many impressive outcomes, which are described in the Science section (pages 7–29) of this report.

We have exceeded our goals in regard to the number of visitors who came to Australia to see our work and the number of invitations we received to address international conferences.

For 2004 we have exceeded the projected KPIs with 30 publications, including one book. Amongst these are 5 publications (or 17%) with particularly high impact factor in *Phys.Rev.Letters*.

Interaction with the partner institutions is intensifying and we expect to be seeing longer and more intensive exchanges of students and staff internationally and within the Centre. As an example, we have formed an International students network with our partners in Paris and Hannover.

At the same time, we have maintained a widespread teaching program at all three Universities, with a total of 18 undergraduate and professional courses in 2004, and have presented our ideas and goals to a wide section of the Australian Physics community. This includes a special Summer School with 60 undergraduate and postgraduate students from across Australia.

AWARDS RECEIVED

Throughout 2004 the following members of the Centre were rewarded with a number of distinctions which indicate the high profile of our staff.

Prof Hans-A. Bachor	Vice Chancellor's Award for Career Achievement ANU
Prof Peter Hannaford	Australian Academy of Science 2004 Lloyd Rees Memorial Lecturer
Prof Peter Drummond	Massey Medal
Dr Kenneth Baldwin	Eureka Prize for Promoting Understanding of Science with 'Science meets Parliament'
Dr Ken Baldwin	Delivered the September Graduation Address at Macquarie University

Ken Baldwin at Macquarie University

Vice-Chancellor Ian Chubb presents Hans-A. Bachor with his Career Achievement Award

Peter Hannaford

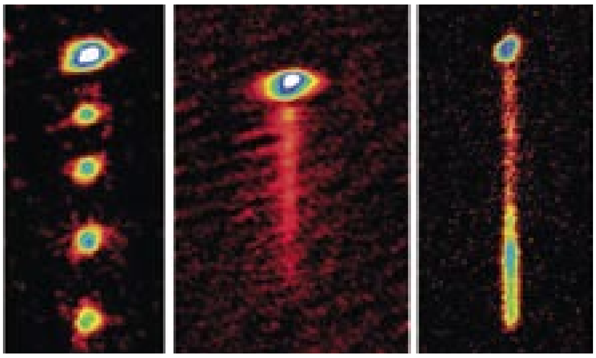
Key Performance Indicators (KPI)

Key Result Area	Performance Measure	Target	Outcome
Research Findings	Quality of publications International Ref. Journals with an impact factor >5	4/29	5/29
	Number of publications/year	20	29
	Number of patents/year	0.3	1
	Number of invitations to address and participate in international Conferences/year#A	4	14
	Commentaries in professional journals National and international/year	3	2
Research Training and Professional Education	Number of postgraduates recruited/year	5	9
	Number of postgraduates completions/year	4	6
	Number of Honours students/year	5	4
	Number of professional courses to train non Centre personnel/year	2	5
	Number and level of undergraduate and high school courses in the Priority area/year	7	12
International, National and Regional Links and Network	Number of International visitors/year	10	18
	Number of national and international workshops/year	1 international 1 national	2 2
	Number of visits to overseas Laboratories	18	42
	Contact with researchers related to the philosophical aspects of Quantum Physics		
End-user Links	Number and nature of commercialisation activities	2	0
	Number of government, industry and business briefings/year	2	2
	Number of Centre associates trained In technology transfer and commercialisation	2	0
	Number and nature of Public Awareness programs	4	5
	Awards		5

PUBLIC RELATIONS/MEDIA

The Centre maintained a high profile in the media with excerpts from the following articles sent to various media outlets during 2004:

April — Australia's First Atom Laser Developed at ANU



ANU Atom Laser

ANU researchers have developed Australia's first atom laser, consisting of a single beam of atoms of the coldest material in the Universe. The atom laser, developed by a team of physicists from the Australian Research Council Centre of Excellence for Quantum-Atom Optics at ANU, produces a beam of matter waves and is potentially far more precise than the optical lasers that are in CD drives and communication technologies. **The Australian Research Council Centre of Excellence for Quantum-Atom Optics** was established in 2003 at ANU and is taking Australia to the cutting edge of atom laser technology, conducting fundamental research which could be an important base for the future of the nation's economy. The laser was developed by a team of physicists including: Dr John Close, Dr Nicholas Robins, Dr Joseph Hope, Dr Craig Savage, Dr Jessica Lye, Mr Simon Haine and Mr Cameron Fletcher.

Television:
Darwin ABD6 State Television News 7:00PM April 8
Sydney ABN2 State Television News 7:21PM April 8
Canberra Prime TV State Television News April 8
Canberra ABC TV State Television News 7:09PM April 8

Radio:
666 ABC Canberra interview 7:38AM April 8
666 ABC Canberra Radio News 9:00AM April 8
891 ABC Adelaide Radio News 9:00AM April 8
ABC Radio South Australia News 9:00AM
Adelaide 5RN Radio News 9:00AM April 8
Triple J Radio News 11:00AM April 8
ABC Northern Tasmania Radio News 11:00AM
936 ABC Hobart Radio News 11:00AM April 8
Hobart 7RN Radio News 11:00AM April 8
ABC Radio Tasmania Radio News 11:00AM April 8
Canberra CA Radio News 3.00pm April 8
Canberra 2CC Radio News 3:00PM April 8
612 ABC Brisbane Radio News 3:00PM April 8
612 ABC Brisbane Radio News 9:00PM April 8
Canberra 2CC Mike Jeffreys 6:50AM April 9
774 ABC Melbourne Radio News 7:00AM April 9
ABC Radio Victoria Statewide News 7:00AM April 9
Melbourne 3RN Radio News 7:00AM April 9
774 ABC Melbourne Radio News 7:45AM April 9

May — Nobel Prize-winner Verifies UQ Physics Theory

The Nobel Prize winning research group of Professor Bill Phillips at the US National Institute of Standards and Technology, this week published an experimental verification of a recent theoretical prediction of Dr Karen Kheruntsyan and Professor Peter Drummond, of the University of Queensland node of the ARC Centre of Excellence for Quantum-Atom Optics. The theoretical work has been carried out in collaboration with Gora Shlyapnikov and Dimitri Gangardt of Ecole Normale Superieure, France.

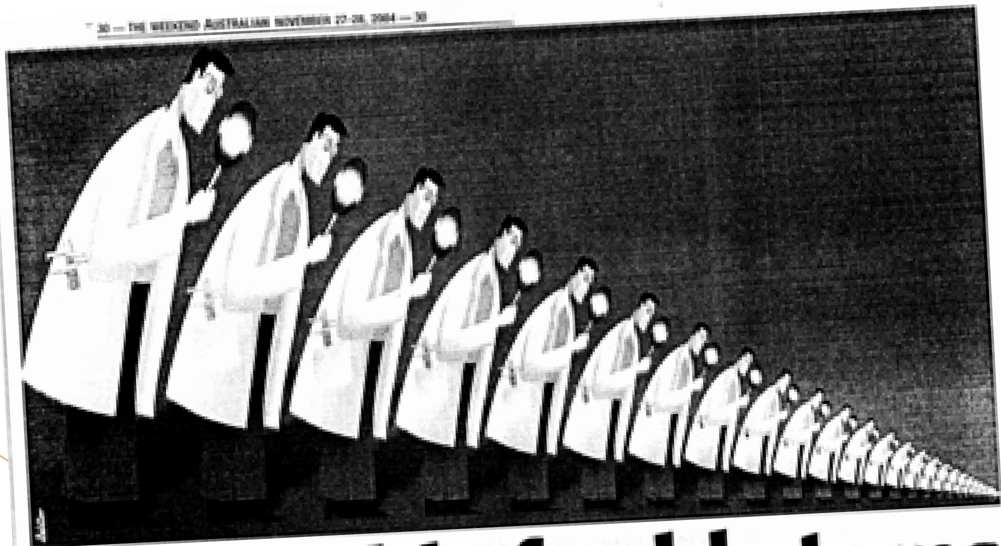
Print
UQ News Online
UQ News

July — Quantum-Optics — What Is It?

The first edition of the book "A Guide to Experiments in Quantum-Optics" sold out quickly around the world. The Australian authors, Prof Hans-A. Bachor, Research Director of the Australian Research Council Centre of Excellence for Quantum-Atom Optics and Associate Professor Timothy C Ralph, have written a second, enlarged edition to keep pace with the rapid development and interest in this field.

Print
AOS News

30 — THE WEEKEND AUSTRALIAN NOVEMBER 27-28, 2004 — 30



Hot world of cold atoms

An ultra-cool wave is sweeping across quantum physics, reports Leigh Dayton

WILLIAM Phillips works in what's definitely a three-dimensional physics laboratory in Gaithersburg, Maryland. But he has spent the past few months stuffing three-dimensional atoms into a one-dimensional world — just to see what happens.

"Weird things happen when you change the dimensions of the world you live in," says the multi-dimensional Phillips, a Nobel laureate physicist and head of the laser cooling and trapping group of the US National Institute of Standards and Technology.

Cooling, trapping, atoms, weirdness and shifting dimensions — if this all seems baffling, just wait. Things are about to get stranger still. That's because Phillips and his misbehaving atoms are part of the hottest new field of quantum physics, cold atoms, also called atom optics. And cold is definitely the operative word, as University of Queensland physicist Peter Drummond explains.

"In the 20th century, the biggest thing in ultra cold physics was liquid helium, which is four degrees above absolute zero," he explains, adding that absolute zero is so cold that even atoms and molecules barely budge. "In the last decade we've gone so far beyond that it's unbelievable. We're now a billion times colder than that."

In other words, scientists have whipped up in their laboratories the coldest material that has existed anywhere in the universe.

As Phillips and Drummond note, at such incredibly cold temperatures the unexpected is expected. That's why physicists worldwide are jumping on the cold atom bandwagon.

"It's like opening up a whole new universe," says Hans Bachor, a physicist with the Australian National University and the driving force behind the new Australian Research Council Centre of Excellence for Quantum Atom Optics, a consortium of scientists with the ANU, UQ, and Melbourne's Swinburne University of Technology.

Phillips, Drummond and Bachor all wax lyrical at the promise of cold atoms, from fundamental research to faster, smaller and more powerful nano-machines and devices. They're not alone. "The possibilities for new science and technologies are mind-boggling at the moment," says Keith Burnett, head of atomic and laser physics at Britain's Oxford University.

The pace of discovery is certainly as breathtaking as the concept of cold atoms. Last year, for instance, the centre became one of just five groups in the world to build an atom laser, a device that fires a stream of all-in-step, frozen atoms — in this case rubidium atoms — so fine that it's invisible to the naked eye.

International teams have also begun to experiment with something called the Bose-Einstein condensate, a strange state of matter that was predicted more than 70 years ago, yet only created experimentally in 1995 when researchers showed that intensely cold atoms behave like waves and form a gigantic matter-wave. The condensates are being used as the source of atoms for the newfangled atom lasers.

Just this year, teams of physicists, including Burnett's, have created super molecules, the largest particles known to follow the mysterious rules of quantum physics. Until now the workhorse of quantum physics was the photon of light.

"It has no mass and the wave-like properties of the photon are particularly easy to see," Drummond says, hinting that another Nobel prize for work on all things cold is tipped for the super-molecule people. Phillips earned his gong for developing methods to cool and trap individual atoms.

With so much intellectual energy flowing, the ARC centre — funded from 2003 to 2007 — is next week sponsoring an international workshop to tap into the hottest developments in this coldest of realms. Phillips and Burnett are on the guest list, along with leaders from France, Canada, Israel and New Zealand.

Bachor is keen to ensure that Australia is not progressively left out when the next generation of scientists bring the theoretical promise of the frontier field in from the, well, cold. That's why the overseas hot shots have agreed to participate in a summer school, sponsored by the centre, for 62 budding physics students from Australian, NZ and Singaporean universities.

"If we want to take on the US and Europe we have to be competitive and we have to co-operate within Australia and New Zealand," says Bachor, who thinks big as well as small. "We need to be a regional powerhouse."

To get a real-world feel of the power of cold atoms, Bachor suggests an intellectual tour of the atom laser. It is, he says, a "scientific toolbox" that will allow scientists to build things such as exquisitely sensitive sensors for nano-machines or futuristic communication systems filled with enormously powerful and vanishingly small quantum chips.

The atom laser could also give existing optical lasers the boot in many everyday applications such as CD and DVD players. That's so, Bachor says, because the beam of matter produced by the laser is potentially far more precise than the beam of light kicked out by optical lasers.

Phillips adds that the kind of precision offered by atom lasers and super-cold atoms would push the bounds of accuracy in applications as diverse as scientific instruments such as interferometers, gyroscopes and even global positing systems and clocks.

"Atomic clocks are the most accurate clocks we've ever had. But the atoms are moving so fast that the time to make the necessary measurements is limited. But by getting the atoms cold they move very, very slowly so we can make the clock even better," Phillips says.

Proving the point, Phillips is deeply involved in an atomic clock space mission scheduled to fly to the International Space Station in 2008. The idea is to study laser-cooled atoms in microgravity. "We're also thinking of using cooled atomic clocks on interplanetary missions or to explore Mars, places where you need more accuracy but you can't update (precision settings) as easily as on Earth."

While such projects are exciting and potentially useful, the real enthusiasm for the cool crowd is the prospect of testing the theories of quantum physics, or mechanics, the system of laws that govern the behaviour of matter and energy at the atomic level. "At the moment, we all believe quantum mechanics is correct. It seems to describe nature with remarkable accuracy," Phillips says. "But we have to test it to see if it's true."

He says Bachor's scientific toolkit can also be applied to solutions to the "thought problems" of great thinkers who didn't have the technology to put their ideas to the test, referring particularly to Albert Einstein.

"The year 2005 is the 100th anniversary of Einstein's annus mirabilis," Phillips observes. "In 1905, he published three papers that revolutionised everything: the photoelectric effect, the Brownian effect and special relativity. We'd like to make accurate tests of his theory, especially gravity," he says.

Here Phillips echoes the sentiments of his colleagues. It's easy to imagine them reciting a scientific version of the well-loved nursery rhyme The House that Jack Built. Cold atoms will be the tools that build the devices to test the theories that Einstein built. If so, they're giving an ironic spin to the quantum world, a universe where things are precisely imprecise. It all makes Phillips's one-dimensional atoms look like intellectual child's play.

Quantum's ripple effect

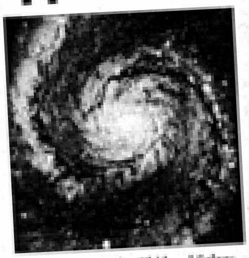
WE live in a quantum universe. According to leading cosmologist and physicist Paul Davies, it's a misconception that the complex field of quantum physics, or quantum mechanics, applies just to the tiny world of molecules, atoms, subatomic particles and the strange things they get up to.

"Increasingly, scientists believe quantum physics is the correct theory of the whole world," Davies says from Macquarie University's Australian Centre for Astrobiology. That is, the whole of reality, the entire universe, behaves according to the weird rules that dictate the maybe this, maybe that quantum behaviour of elementary particles of energy and matter.

"Today the universe is very big, but once it was very small — small enough for quantum effects to be very important," Davies explains. "Most cosmologists believe that the birth of the universe was a quantum event. We can't understand how the universe came to exist except as a quantum mechanical process."

Moreover, after that "originating event" roughly 13 billion years ago, quantum mechanics continued to drive cosmic history. For instance, in the first trillion trillion trillionth of a second, the universe enormously inflated in size to become very smooth, and so-called "quantum fluctuations" imprinted tiny but conspicuous rumples on the smooth background. "These quantum ripples can be seen today, writ large in the sky, as hot and cold splodges in the heat radiation left over from the big bang," Davies says.

Those ripples were the seeds of the galaxies. And because everything from plants to people is made of material created in the explosions of stars, Davies says we owe our existence to those "ripples at the edge of time" and to the quantum mechanics that built them.



Creative forces: The Whirlpool Galaxy

ACQAO publicity

August — ACQAO Deputy Director Wins the Eureka Prize

Dr Ken Baldwin, Deputy Director of the Australian Research Council Centre of Excellence for Quantum-Atom Optics has won the 2004 Australian Government Eureka Prize for Promoting Understanding of Science for initiating and championing the annual FASTS "Science Meets Parliament".

Bob McMullan MP, (L) Gary Nairn MP (R) congratulate Ken Baldwin, Eureka Prize winner

Television
ABC News Online

Print
The Australian
Science Wise
On Campus
Material Monthly
AOS News
Australian Physicist

Radio
Canberra ABC 666

November — Launch of the Book "Quantum Squeezing"

Peter Drummond, UQ Node Director of the ARC Centre of Excellence for Quantum-Atom Optics and co-author Z. Ficek launched their book at the University of Queensland.

Print
UQ News

November — Hot World of Cold Atoms

An ultra-cool wave is sweeping across quantum physics, reports Leigh Dayton after interviewing Professors Bachor, Drummond (ACQAO) and Professors Phillips and Burnett (ACQAO Advisory Board members).

Print
The Weekend Australian November 27–28
(see page 38)

December — 2004 Massey Medal

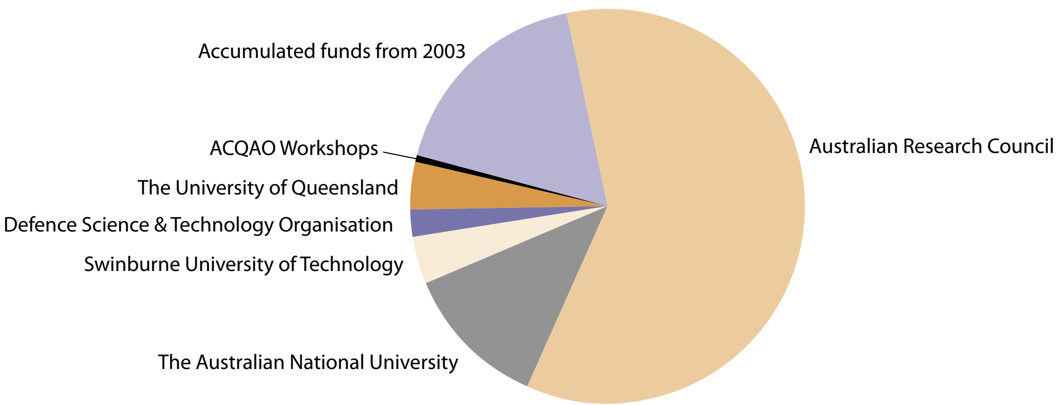
2004 Massey Medal Awarded to Peter Drummond, Director UQ Node of ARC Centre of Excellence for Quantum-Atom Optics for his work on many-body theories and quantum optics.

Print
AOS News

Sir John Enderby, President of IOP, UK presents Prof Peter Drummond with the Massey Medal

ACQAO INCOME 2004

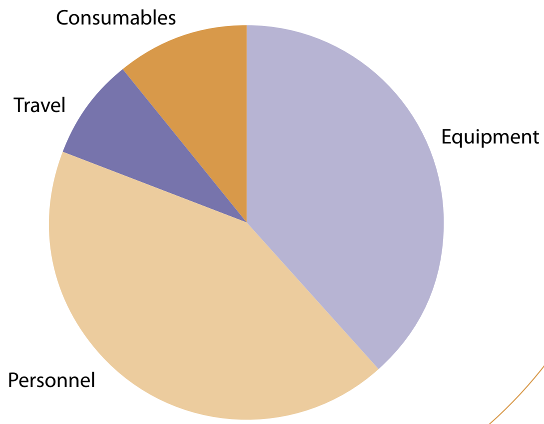
Accumulated funds from 2003	$676,096.00
Australian Research Council	$2,294,245.00
The Australian National University	$456,000.00
Swinburne University of Technology	$150,000.00
Defence Science & Technology Organisation	$76,500.00
The University of Queensland	$150,000.00
ACQAO Workshops	$18,227.00
TOTAL INCOME	**$3,821,068.00**



Note: Queensland State Government funding for 2003 and 2004 of $300,000 to be paid in the first half of 2005. The University of Queensland has invoiced the State of Queensland for these funds.

ACQAO EXPENDITURE 2004

Equipment	$1,131,320.00
Personnel	$1,254,346.00
Travel	$245,894.00
Consumables	$314,833.00
TOTAL EXPENDITURE	**$2,946,393.00**



ACCUMULATED FUNDS	**$874,675.00**

ACQAO 2004 PERSONNEL

Below is a list of all Staff and Students including Honours/Undergraduates with project work in ACQAO during 2004.

ANU Fac Node
Prof Hans-A. Bachor
Ms Ruth E Wilson
A/Prof Craig Savage
A/Prof John Close
A/Prof Ping Koy Lam
Dr Joseph Hope
Dr Mattias Johnsson
Dr Nick Robbins
Dr Laurent Longchambon
Dr Cristina Figl
Mr Max Colla
Mr Magnus Hsu
Mr Sebastian Wuester
Mr Simon Haine
Mr Gabrial Hetet
Ms Adele Morrison
Ms Amy Peng
Mr Cameron Fletcher
Mr Andrew Ferris
Mr Vincent Delaubert
Ms Katie Pilypas
Ms Tracy Slatyer

ANU IAS Node
Dr Ken Baldwin
Prof Yuri Kivshar
Dr Elena Ostrovskaya
Dr Chaohong Li
Dr Andrew Truscott
Dr Tristram Alexander
Dr Robert Dall
Ms Wendy Quinn
Mr Tom Hanna
Ms Beata Dabrowska
Ms Pearl Louis

SUT Node
Prof Peter Hannaford
Prof Fel Andrei Sidorov
Prof Fel Russell McLean
Prof Fel Tien Kieu
A/Prof Bryan Dalton
Dr Wayne Rowlands
Dr Gráinne Duffy
Dr Brenton Hall
Dr David Low
Mrs Sharon Jesson
Mr Shannon Whitlock
Mr Falk Scharnberg
Mr Heath Kitson
Mr Jürgen Fuchs
Mr Michael Vanner
Mr Holger Wolff
Mr Gopisankararao Veeravalli

UQ Node
Prof Peter Drummond
Dr Karen Kheruntsyan
Dr Matthew Davis
Dr Joel Corney
Dr Margaret Reid
Dr Xia-Ji Liu
Dr Murray Olsen
Dr Paul Cochrane
Ms Diane Hutton
Mr Timothy Vaughan
Mr Chris Foster
Mr Eric Cavalcanti
Mr Thomas Clement
Mr Benjamin Perret
Mr Brian Kash
Mr Piotr Deuar

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Australian Research Council Centre of Excellence for Quantum-Atom Optics

http://www.acqao.org

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