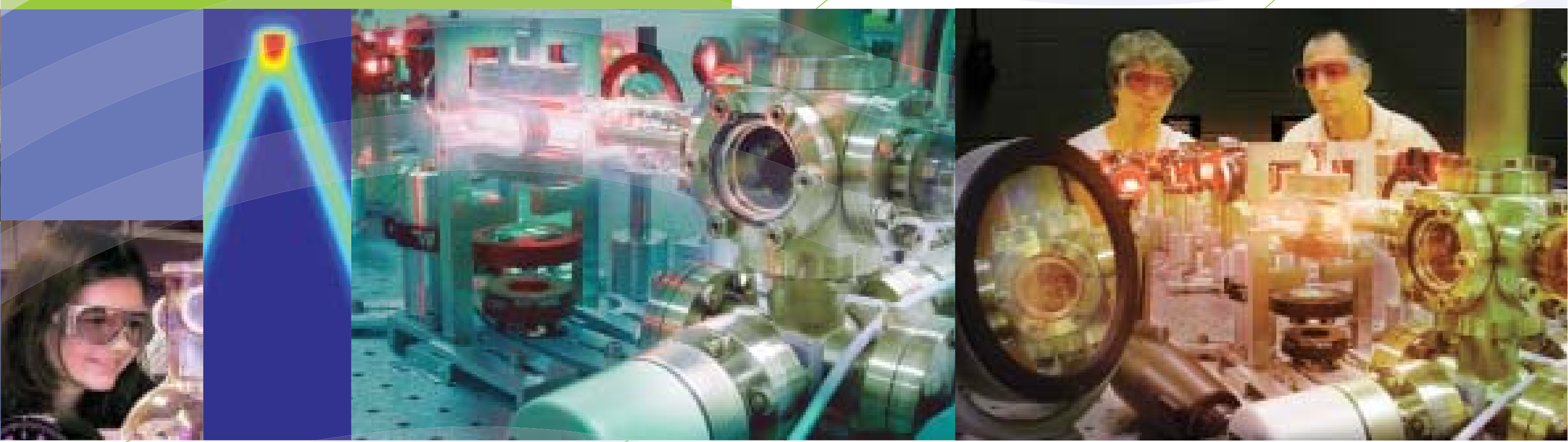

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report 2004

THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian Government

Australian Research Council

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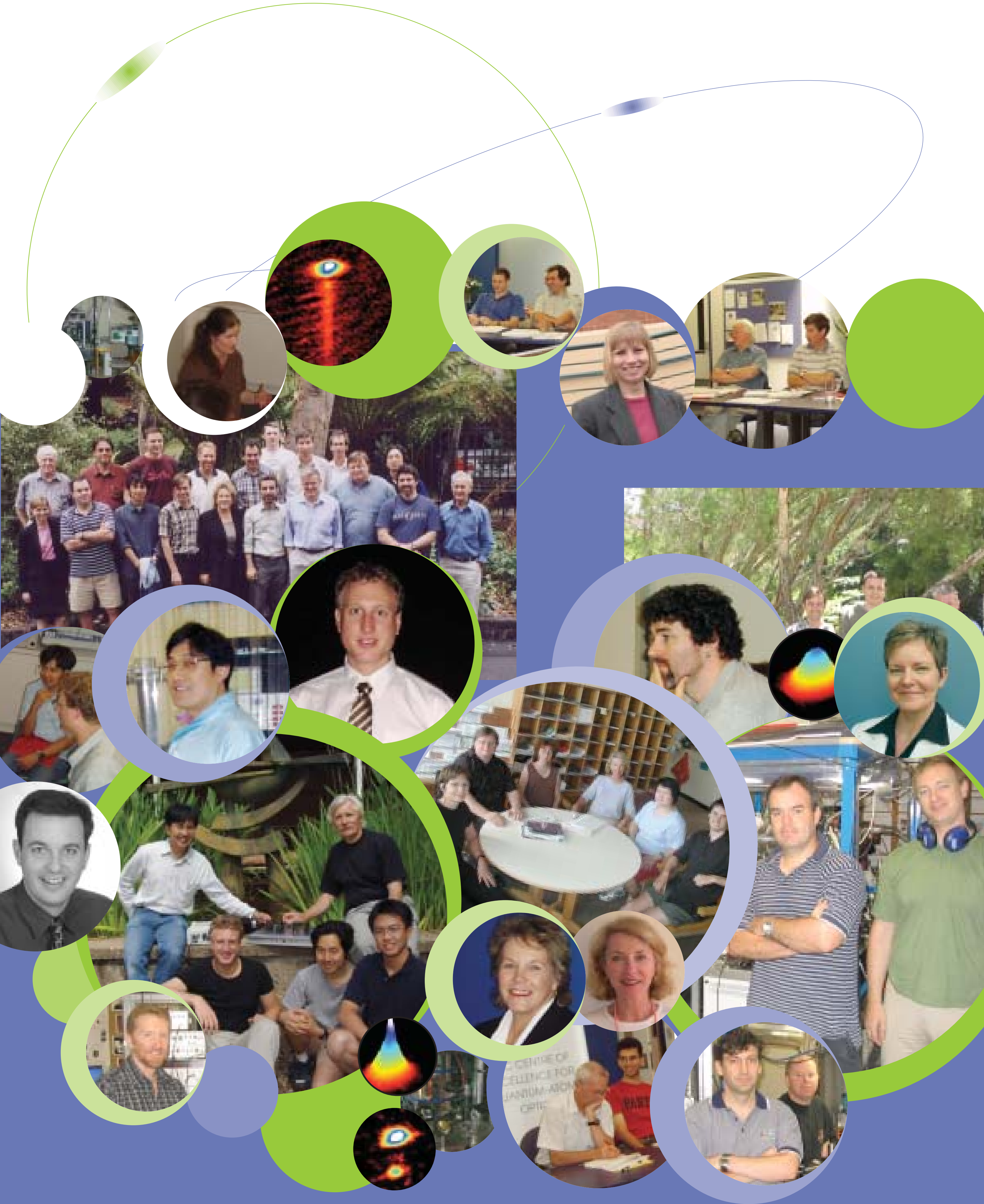


FOREWORD

Professor Hans-A Bachor

Quantum science will play a major role in future technology and eventually affect our daily lives.

One area will be the application of optical and wave effects of not only light but atoms. Scientifically we are now able to investigate the quantum behaviour of larger objects, involving thousands and millions of atoms and see the transition from the microscopic world of a few particles to the macroscopic world of the classical. Technically we are now able to use the concept of entanglement that was just an idea in the 1930s, and use it in practical applications, such as a communication system.

We now have the technology for cooling atoms to unimaginably low temperatures and for creating Bose-Einstein condensates (BECs). We are at the threshold of turning this fundamental science into practical applications over the next two decades.

The Australian Research Council Centre of Excellence for Quantum-Atom Optics is one of Australia's contributions in the rapid development of quantum science that is happening around the world. The Centre concentrates on fundamental science questions. It combines our well-established track record in quantum optics with our leading groups in atom optics and laser cooling into one team with common goals. We are combining pioneering theoretical work with experimental projects. The Centre brings together scientists working in three cities, the Australian National University (ANU) in Canberra, the University of Queensland (UQ) in Brisbane and Swinburne University of Technology (SUT) in Melbourne and links them with scientific partners in Europe and New Zealand.

The Centre of Excellence is part of the vision of the Australian Research Council to promote excellence in the most successful fields of research and gives us the opportunity to become players in the international arena. The funding and support provided by the Australian Research Council, the three Universities and governments in Queensland and the Australian Capital Territory will allow us to tackle ambitious research projects, to have an intensive exchange of people, to purchase the required research equipment and to provide opportunities for young scientists and reach out into the community.

This is our first annual report. The structure of the Centre, the staff, our research plans and our achievements in 2003 are described within. I hope it gives you an insight into this exciting and stimulating venture to lay the foundations for some of the technologies of the future.

Hans-A. Bachor

Professor Hans-A Bachor
Research Director

QUANTUM-ATOM OPTICS

What is it? — 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 in this type of classical optics.

In contrast quantum optics adds the effects based on the quantization, or the particle nature, of light to this, exemplified in the statistical behaviour of photons.

It has become easier over the years to isolate such quantum effects and they appear more and more as a limit in the quality or sensitivity of optical instruments. In addition, quantum optics offers new possibilities for the communication of information with light.

The field of Photonics, which is essentially based on classical optics, will soon benefit from the advances in quantum optics. Australia has long held a strong international research profile in this field, in particular in 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. The challenge is to use entanglement of not only single particles but whole macroscopic systems.

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 Centre's ANU researchers have already built sources that produce strong entanglement. 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 can report impressive new results — the first demonstration of a two dimensional quantum laser pointer [1].

Atom-Optics

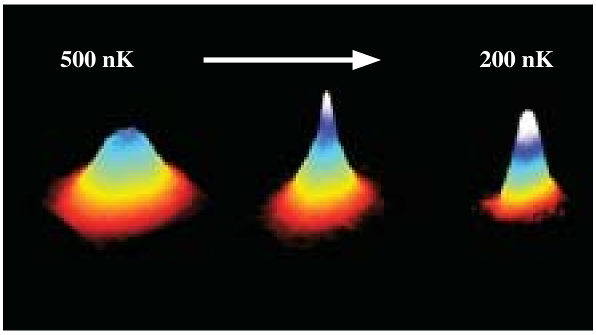
Atom optics, by comparison, is a field where we find that atoms not only have the properties of particles that move and collide with each other, but also have properties, which require a wave description.

Groups of atoms can be manipulated, cooled, stopped and trapped until they reach such a low temperature that the wave and quantum effects dominate.

It has been shown some years ago that the deBroglie 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, the bosonic atoms such as Rb87, Cs137, He4 will make a rapid transition into a new state of matter once they cool below a critical temperature. This is a so-called Bose-Einstein Condensate (BEC) that has properties vastly different from a thermal cloud of atoms.

Australia Produces a BEC

As of January 2004, the only apparatus in Australia that produces a BEC resides with our Centre.



Experimental data for transition from a thermal cloud to BEC

We have been studying BEC properties in detail and we are developing the technology to vastly reduce the complexity and size of the apparatus. This is based on unique technology within the Centre which uses permanent magnets with micron-sized structure to guide, trap and condense the atoms.

This technology will allow us to build small, reliable BEC instruments which can be developed into robust and very sensitive sensors, based on atom interferometry.

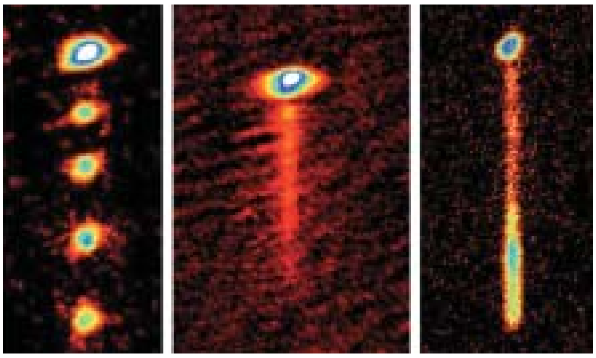
In addition we want to extend the work in Europe by producing a BEC from metastable Helium (He*) atoms. Within the Centre we have extensive experience in generating, collimating and trapping He* and we have experience in detecting individual He* atoms. Our goal here is to build a measurement system for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

We also want to extend the generation of a BEC from atoms to molecules. First results were very recently reported in Europe and the USA on generating and Bose-condensing ultracold molecules consisting of bosonic atoms. We wish to perfect this technique and demonstrate some of the novel reaction 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.

During 2004 we produced a pulsed atom laser [2], following the earlier examples of such devices reported in the literature and we now have detailed plans to extend this to a continuously pumped atom laser. Special diagnostic techniques are being developed to demonstrate the unique quantum properties of the atom laser beam.



Pulsed and continuous atom laser results

Linking Quantum and Atom Optics

This Centre combines, in a unique way, quantum and atom optics. 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 storage for quantum information.

The parallel experiments on quantum information communication and cryptography are carried out independently at the ANU outside the Centre.

All these experimental goals are supported by a very strong theory core, which combines the expertise of world-renowned researchers. The different techniques and expertise from quantum optics, field theory and non-linear optics are combined within one powerful group of scientists who guide and support the experimental work.

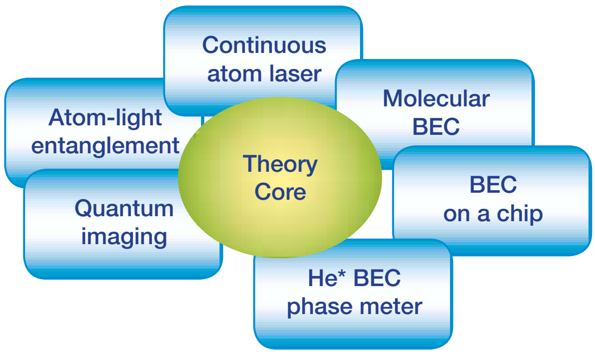
In some cases the theory is well ahead of the experiments and we have projects, such as the relationship of Bosonic systems at low dimensions, and the study of matter waves in optical lattices and periodic structures which can lead us to future experiments.

Scientific Tools for the Future

The goal of the Centre is to provide the scientific tools required to develop quantum and atom optics into a whole new field of 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 concepts from quantum and atom optics, by linking the leading scientists in Australia and by developing an exchange with our partners in Europe, who represent some of the most productive groups in this field.

In this way the Centre is present in the international arena and ensures that the development and transfer of optical quantum technology will remain accessible to Australia.



Our research goals

THE NODES

The Centre combines many of the leading scientists in quantum and atom optics in Australia. They and their laboratories have all remained in their individual locations and we are linking them through joint scientific work, the sharing of expertise and equipment, the exchange of people, and the employment of additional staff and students working in several locations.

ANU FACULTY OF SCIENCE

The Centre headquarters is located at the ANU, in the Faculty of Science where the ACQAO meeting facilities, the Research Director (Hans-A. Bachor), the Chief Operations Officer (Ruth E.Wilson) and Research Officer (Max Colla) reside.

In the same location we have the research node which carries out experimental work on rubidium (Rb) BEC, Rb atom lasers and the development of new BEC diagnostic techniques (John Close), as well as quantum imaging, spatial entanglement and atom light entanglement (H-A Bachor and Ping Koy Lam).

Faculty of Science team

This is supported by the corresponding theory (Craig Savage, Joe Hope) that concentrates on the properties of coherent atom sources, quantum feedback and macroscopic quantum effects.

ANU INSTITUTE OF ADVANCED STUDIES

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

He BEC team at ANU*

been established for the metastable helium (He*) experiment (Andrew Truscott and Ken Baldwin, Deputy Directory). The theoretical group has world-leading experience in non-linear physics and photonics bandgap structures (Yuri Kivshar, Elena Ostrovskaya) and their focus is on matter wave properties in optical lattices.

The quantum properties of such periodic structures can be far more complex and useful than the single wave function of a BEC.

Theory team at ANU IAS

UNIVERSITY OF QUEENSLAND

Theory team at UQ

At the University of Queensland (UQ) we have a node located in the Science Faculty that is led by pioneering theorists (Peter Drummond — Node Director, Margaret Reid, Karen Kheruntsyan, Joel Corney and Matthew Davis). Their work includes the numerical and quantum phase-space methods for the simulation of BECs, ultracold molecule formation in BECs, quantum correlations in one dimensional Bose gases, and the development of dedicated software.

SWINBURNE UNIVERSITY OF TECHNOLOGY

At Swinburne University of Technology (SUT), the Centre has two experimental projects in laboratories located within the School of Biophysical Sciences and Electrical Engineering with Peter Hannaford as Node Director.

SUT has pioneered the use of micro-structured permanent magnet structures which will be used to produce BECs on a chip (Andrei Sidorov, Russell McLean and Peter Hannaford).

In parallel, an experiment for the generation and Bose condensation of Cs molecules is in preparation (Wayne Rowlands and Peter Hannaford). A theory group supports both projects (Bryan Dalton, Tien Kieu). In addition to the CIs mentioned here, the Centre includes a number of research fellows, postdoctoral fellows, graduate students and visiting fellows. All of their names are listed on page 38.

Brainstorming session SUT and UQ

Wayne Rowlands

Peter Hannaford and Tom Hanna

Shannon Whitlock

GOVERNANCE

While the Research Director, Hans-A Bachor, is responsible for the overall science direction and performance and 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 meeting. 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 organise, given by demand, scientific discussions, workshops and brainstorming sessions that bring together members of the Centre from all locations.

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.

We are fortunate to have an advisory board of exquisite expertise. Our international science advisors, Alain Aspect (Inst. d'Optique in Orsay), Keith Burnett (Oxford), William Phillips (NIST Maryland), Crispin Gardiner (Wellington) and Eugene Polzik (Copenhagen) have extensive experience and provide leadership in all fields of quantum and atom optics. Our national board members, Senator Gary Humphries, Bob McMullen MP, Steven Duvall (Intel), Bruce Whan (Swinburne) and David Wilson (DSTO) provide experience in the field of liaising with the Australian public and end-users of our research.

This advisory board has met during the opening of our Centre in Canberra in July 2003 and provided initial advise to all CIs. The first detailed evaluation will occur in December 2004.

Left to right, Advisory Board Professors Peter Drummond, Hans-A Bachor, William Phillips, Alain Aspect, Crispin Gardlner, Eugene Polzik and Peter Hannaford

Centre Management Meetings

CI meeting	All CIs & COO	Bi-annual	2/03 Caloundra 7/03 Cairns 12/03 Melbourne
Executive Board	Res Dir. & COO Node Directors	quarterly	4/03 Canberra 7/03 Canberra 10/03 Canberra
Advisory board	International & national members	annually	7/03 Canberra
International Workshop	Centre & partners other AUS groups	Bi-annual	2/03 Caloundra 7/03 ICOLS
Individual Project &group	Staff & students visitors	fortnightly	
IP committee	Node directors Universities	annually	

Future Directions for 2004

The scientific goal is to make the most progress in all six experimental projects (see page 3). We need to complete our new laboratories, install all major equipment and achieve the initial milestones. At the same time the links between the experimental groups will be intensified to allow for the exchange of expertise and equipment as well as the links between the theory groups and experiments.

This will be achieved through intensive discussions and work in small, dedicated teams. All staff will be established by mid-2004 and we will operate at maximum speed.

Demonstrating a quantum laser pointer

N. Treps [1], N.Grosse [1], W.P.Bowen [1], C.Fabre [2], H-A.Bachor [2] and P. K.Lam [2]
[1] *ACQAO, Faculty of Science, Australian National University, Australia*
[2] *Laboratoire Kastler Brossel, Universite Pierre et Marie Curie, case 74, 75252 Paris cedex 05, France*

Measuring the pointing direction of a laser beam is one of the most direct and sensitive applications of a laser. It can use it to detect various weak physical effects such as variations of the electromagnetic field, the displacement of cantilevers etc. Once this is done at the quantum noise level this type of measurement is one of the simplest demonstrations of the quantum properties of an optical imaging systems. The direction of the laser beam is detected as position on a quadrant photo detector with elements (a, b, c, d) and the combined photocurrents $I_x = (I_a + I_b) - (I_c - I_d)$ and $I_y = (I_a + I_c) - (I_b - I_d)$, see Fig. 1. The limits by which these currents, and thus the position d, can be detected are given by the quantum noise. In the case of a standard TEM$_{00}$ mode this limit is given by $d_{QNL} = \sqrt{\pi/8}\, w_0/\sqrt{N}$ where N is the number of photons detected in one measurement time interval [1, 2]. Our goal was to surpass this limit using light with quantum correlations.

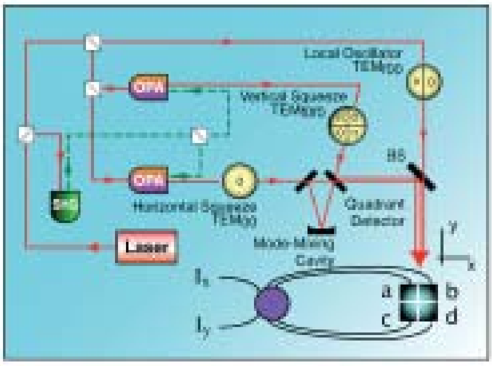


Figure 1: Measuring the position of laser beam and creating a spatially squeezed light

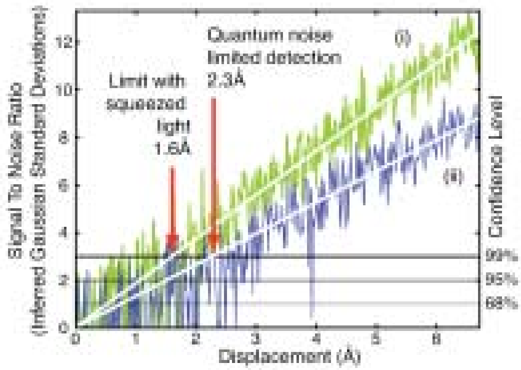


Figure2: Improved sensitivity with squeezed light

The intellectual challenge was to find a way to convert the conventional squeezed light, which has quantum correlations in time, into beams that have the appropriate 2D spatial quantum correlations. This was solved by C.Fabre et al. [1] who proposed to use beams with asymmetric phase distributions, that means phase shifts of π, along the x and y coordinate. The experimental challenge was to combine the two squeezed beams, which have a complex spatial distribution, without losses with a strong coherent beam. This was achieved by using a resonant ring cavity and its property that a beam of uniform phase (TEM$_{00}$) is fully transmitted while a beam with complex phase distribution is reflected by the cavity, as shown in Fig. 1. [3]

We used two squeezed beams generated by separate Optical Parametric Amplifiers (OPA) to generate a squeezed beam with noise suppression of $>$ 2 dB in x and y direction. To show the improved sensitivity we measured the periodic displacement, or wiggle, of a laser beams at about 5 MHz which was introduced by a mirror driven with a piezo crystal. We determined the quantum limit d_{qnl} as about 0.23 nm for our parameters and showed that we could improve this sensitivity down to 0.16 nm in the x-direction and simultaneously to 0.18 nm in the y-direction. [3] as shown in Fig 2. This is the first demonstration of a spatial measurement beyond the quantum noise limit.

References

[1] C.Fabre, J.B.Fouet, A.Maitre, Opt. Lett. **25**, 76 (1999)

[2] N.Treps, U.Andersen, B.C.Buchler, P.K.Lam, A.Maitre, H-A.Bachor and C.Fabre, Phys.Rev.Lett. **88**, 203601 (2002)

[3] N.Treps, N.Grosse, W.P.Bowen, C.Fabr, H-A.Bachor, P.K.Lam Science **301**,940 (2003)

Classical fluctuations and flux: The limits of multi-state atom lasers

N. P. Robins, C. M. Savage, J. E. Lye, C. S. Fletcher, S. A. Haine, J. J. Hope and J. D. Close
ACQAO, Department of Physics, Australian National University, Australia.

In June 2003, the experimental atom optics group in the Department Physics at ANU produced its first pulsed and continuous atom lasers (see figure 1 below) and studied classical fluctuations on the output beam. Although classical fluctuations are deterministic, they have real detrimental effects in precision measurements. There is a large literature for example characterising the classical fluctuation spectrum in solid-state optical lasers. In these lasers, the spectrum of classical fluctuations is dominated by pump noise at low frequencies and the relaxation oscillation at higher frequencies. Characterization of the relaxation oscillation has allowed the implementation of devices such as "noise eaters", used in quantum optics labs around the world, to feedback to the laser, suppress classical fluctuations and achieve or surpass, through squeezing, the shot noise limit. Alternatively, many optical experiments are designed to avoid classical fluctuations of this kind either by moving the signal to a higher frequency band by modulation, and/or the use of an RF spectrum analyser. Either way, the classical fluctuation spectrum must be well characterised for these approaches to succeed. Similarly, the characterisation of classical fluctuations, particularly those that are inherent to out-coupling, is essential if atom lasers are to become a useful tool in precision measurement.

In the experimental work on atom lasers completed this year, we made the first observation and study of classical fluctuations on an atom laser beam that are an unavoidable result of state changing out-coupling. We found agreement between our experimental results and a full 3D Gross-Pitaevskii model with no adjustable parameters, and showed that at high flux, classical fluctuations increase with increasing flux. That we can achieve agreement between a 3D theory including all Zeeman states and experiment is significant. It is highly likely that the much sought-after pumped atom laser will operate under rather specific conditions of scattering length, temperature and number density, and experiments will need to be guided by accurate theoretical models that must be validated if we are to trust their detailed predictions. Characterising these fluctuations is the first step towards quantum noise limited measurement with atom laser beams. This work has been submitted for publication to Physical Review Letters.

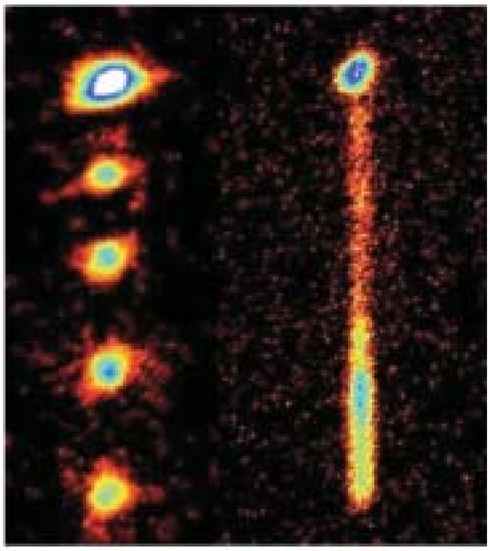


Figure 1: Typical pulsed and continuous atom lasers produced at ANU. The beams are 1.1 mm long. The condensates contain 10^5 atoms at a temperature of 190 nK.

Atom laser pumping through continuous evaporation

J.J. Hope[1] and M. J. Davis[2]
[1] *ACQAO, Department of Physics, Australian National University, Australia.*
[2] *ACQAO, School of Physical Sciences, University of Queensland, Australia.*

One of the major goals of the Centre is to produce a continuously pumped atom laser. The key advantages of such a device are mode selectivity and the possibility of gain-narrowing. In a gain-narrowed laser, a higher pumping rate both increases the total flux and reduces the linewidth of the output, producing a dramatically increased spectral flux. The required element that is missing from current experiments is a saturable pumping mechanism that operates at the same time as the damping.

The two essential steps towards providing a continuous pumping mechanism for an atom laser are the provision of atoms from an external source to the atomic trap, and then a process that causes at least some of those atoms to make an irreversible, stimulated transition into the BEC. There are multiple proposals for the delivery of ultracold atoms to a BEC, most of which depend on having at least one extra trap for a spatially separated laser cooling stage [1]. Recently, sequential reloading of a BEC was achieved using optical tweezers [2]. The irreversible, stimulated transition of the second stage is equivalent to a cooling step.

The only method that has successfully cooled an atomic sample to BEC is evaporation, which couples the BEC to a lossy thermal reservoir via atomic interactions. This method has the advantage that it can be performed without the presence of resonant light, but the obvious disadvantage that it relies on the system approaching thermal equilibrium, and will therefore be reversed by the addition of atoms above the condensate temperature. We have used model based on quantum kinetic theory (QKT) to show that evaporative cooling can be made to operate in a continuous fashion for certain experimental parameters.

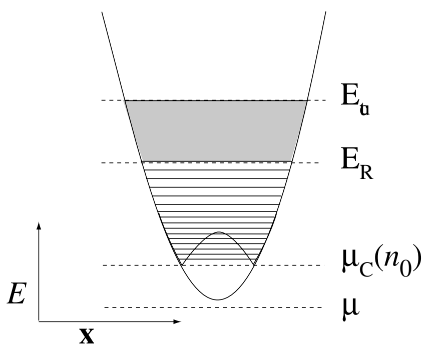


Figure 1: Energy level diagram

QKT has been highly successful in modelling condensate growth [3]. Its success is based on combining a detailed model of the low-lying energy states near the condensate mode (called the condensate band) with a Boltzmann model of the high energy modes. The figure on the left is a schematic energy level diagram showing the chemical potentials of the reservoir gas μ and the condensate mode $\mu_C(n_0)$, the evaporation energy E_c and the boundary E_R between the condensate modes and the reservoir modes.

Further modelling will produce a detailed analysis of the requirements on the reservoir atoms in order for efficient atom laser pumping to occur. An almost identical calculation will used to model the results of a planned experiment at ANU, where the condensate will undergo weak replenishment from a large, uncondensed atomic cloud.

References

[1] J. Williams *et al.*, Phys. Rev. A **57**, 2030 (1998); S.Bhongale and M.Holland, Phys. Rev. A **62**, 043604 (2000); L. Santos, F. Floegel, T. Pfau and M. Lewenstein, Phys. Rev. A **63**, 063408 (2001).
[2] A.P.Chikkatur *et al.*, Science **269**, 2193 (2003).
[3] M. J. Davis, R. J. Ballagh and C. W. Gardiner, Phys. Rev. A **62** 063608 (2000), and references therein.

Control and feedback to Bose-Einstein condensates and atom lasers

S.A. Haine, A.S. Bradley, A.J.Ferris, J.D. Close and J.J. Hope
ACQAO, Department of Physics, Australian National University, Australia.

For an atom laser to have minimum linewidth and hence maximum spectral flux, it must be continuously and come to steady state in single mode operation. In single mode operation the linewidth of the atom laser will be limited by quantum noise and must be calculated using quantum field models. Under particular forms of continuous pumping, these models show that a single mode atom laser exhibits gain-narrowing, and should therefore demonstrate the high spectral brightness of a modern optical laser. Our work published early in the year also shows that it is surprisingly simple to calculate the linewidth for these devices even in the case of non-Markovian behaviour [1]. This is an extension of the normal Schawlow -Townes limit to non-Markovian lasers.

In general, however, there is no guarantee that the modal behaviour of an atom laser will exhibit stability, so may not operate in the single mode regime. We investigated the stability and complex multimode behaviour that will limit the linewidth of the atom laser, with a semiclassical model using Gross-Pitaevskii-like equations that include pumping and loss due to inelastic atomic collisions.

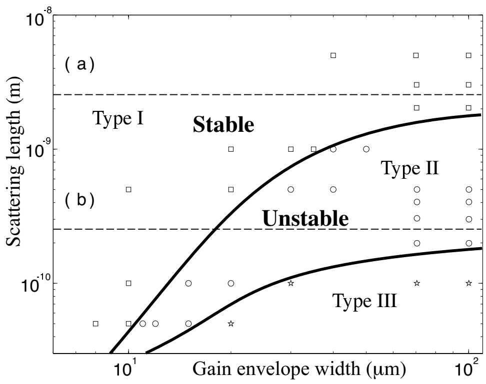


Figure 1: Stability as a function of gain envelope width and scattering length.

We found that the behaviour became unstable below a critical value of the scattering length [2]. This behaviour was due to a higher net gain into the higher energy modes, as these modes were subject to less inelastic loss. Above a critical value of the scattering length however, the ground state became the mode favoured by this gain competition, and hence the atom laser became stable. As quantum noise and classical noise scale oppositely with scattering length, there would be an optimum scattering length and a fundamental limit to atom laser linewidth. We then found that a spatially dependent pumping mechanism can stabilise the atom laser for a value of the scattering length in the unstable regime, and may drastically improve the fundamental limit to the atom laser linewidth.

We introduced a generalised method of using feedback to control multimode behaviour of Bose-Einstein condensates in an arbitrary potential. We found that for any available control, there is an associated moment of the atomic density and a feedback scheme that will remove energy from the system while there are oscillations in that moment [3]. We have demonstrated these schemes by considering a condensate trapped in a harmonic potential that can be modulated in strength and position. The formalism of our feedback scheme also allows the inclusion of certain types of nonlinear controls. If the nonlinear interaction between the atoms can be controlled via a Feshbach resonance, we show that the feedback process can operate with a much higher efficiency.

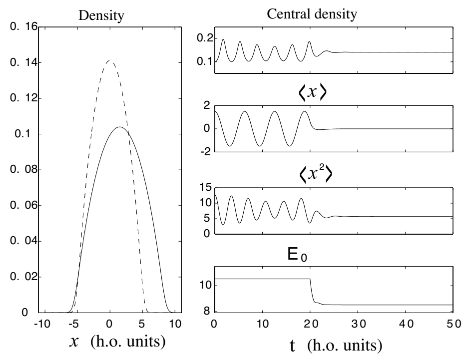


Figure 2: BEC experiencing feedback to the trap strength and position.

References

[1] A.S.Bradley, J.J.Hope and M.J.Collett, Phys. Rev. A **68**, 063611 (2003).
[2] S. A. Haine and J. J. Hope, Phys. Rev. A **68**, 023607 (2003).
[3] S. A. Haine, A. J. Ferris, J. D. Close and J. J. Hope, *to appear in Phys. Rev. A.*

Non-destructive detection of Bose-Einstein condensates

J.J. Hope, J.D. Close and J.E. Lye
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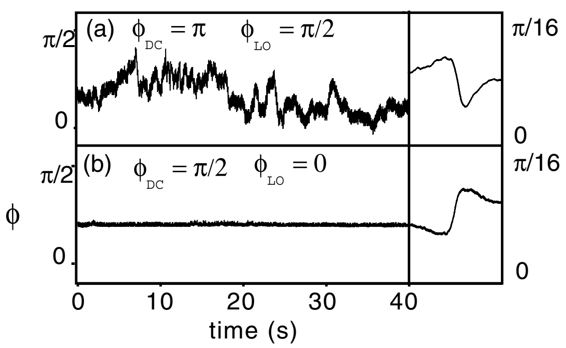
There are a large number of experiments on ultra-cold atoms that require detection that is not only sensitive, but also non-destructive. A major difficulty is that at those energies, a single photon recoil can be regarded as quite destructive. All optical techniques used to probe the properties of atoms have been based on absorption or dispersion. For these systems optical detection of density can only be non-destructive if it does not cause any spontaneous emission, and therefore the atoms must have negligible excited state population. By this criterion, absorption is clearly a destructive measurement technique for atoms, as the signal is directly proportional to the amount of spontaneous emission from the atoms, and therefore even when the detection is shot-noise limited, the total signal to noise ratio (SNR) is proportional to the square root of the spontaneous emission rate. Less obviously, the SNR due to a shot-noise limited measurement of the phase shift of a coherent beam passing through an atomic sample is exactly the same as an absorptive measurement in the optically thin limit. In current detection systems, the only advantage of measuring the phase shift is that it is always possible to reach the optically thin regime by detuning from the atomic resonance, but once this condition is satisfied, no further improvements in the SNR can be achieved. This scaling was described along with a practical analysis of a wide range of detection schemes [1].



An experimental trace of an offset Sagnac showing 15 dB noise suppression (from [2]).

The fact that the theoretical limits imposed by shot noise are linked to the destructiveness of the detection method does not reduce the difficulty of making an interferometric measurement at the shot noise limit in the first place. There are many technical issues involved in choosing a particular scheme, and the figure on the left shows the stability of an offset Sagnac interferometer [2]. This system combined the benefits of a separated path interferometer with a geometrically stable configuration. Further experimental investigations are being carried out.

The equivalence of an optically thin absorption measurement with a dispersive measurement of density was based on a two-level atom interacting with a single field. The fact that in three-level systems with a strong driving field, a probe field can experience finite phase shift with no absorption made it seem possible that multi-level schemes may provide a superior measurement of the atomic density without increasing the spontaneous emission rate. We demonstrated a theorem that shows that there is a fundamental limit for the non-destructive detection of atoms using a shot-noise limited measurement with an arbitrary number of coherent fields [3]. Furthermore, this is the same limit as given by the two-level atom interacting with an off-resonant laser. This theorem was proved using a fully quantum mechanical method of calculating the phase shift of a light beam, which allows it to be calculated in a non-linear system consisting of any number of laser fields coupling to any number of atomic transitions. 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.

References

[1] J. E. Lye, J. J. Hope and J. D. Close, Phys. Rev. A. **67**, 043609, (2003).
[2] J. E. Lye, J. J. Hope and J. D. Close, *to appear in Phys. Rev. A*.
[3] J. J. Hope and J. D. Close, *quant-ph/6308153*.

Rapid real time detection of cold atoms with minimal destruction

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Bose Einstein condensates (BEC) of dilute gases hold great promise in applications from precision measurement with atom lasers, to quantum computing using multiple condensates held in trap arrays [1]. Observation and manipulation of the motional states of these systems requires detection methods that avoid or minimize the spontaneous emission that leads to heating and destruction of the condensate. In two recent papers, it was shown that there is a limit to the signal to noise ratio (SNR) achievable in any single-pass optical measurement using classical light [2, 3]. Phase contrast imaging as implemented by the MIT group is a minimally destructive technique that has been demonstrated on BEC [4]. Spatial heterodyne imaging similarly satisfies the criterion of minimal destruction and, although it has not been implemented on BEC, it has been tested on cold atoms [5]. Polarization contrast imaging satisfies the criterion of minimal destruction under some conditions [6]. These techniques detect the phase shift imparted on a laser beam rather than the absorption of the beam. The low level of destruction (spontaneous emission) of these techniques provides a continuous probe of condensate dynamics bypassing the need for extreme shot to shot reproducibility in a complicated BEC experiment. All these techniques rely on CCD cameras which, compared with photodiodes, are slow.

The minimally destructive detector we have developed is based on photodiodes and is capable of capturing dynamics orders of magnitude faster than is possible with current CCD technology[7]. This detector opens up the study of a whole host of fast dynamics in BEC, such as the evolution of different components in spinor condensates that occur on time scales of microseconds or faster. Photodiode-based detection schemes for BEC are compatible with the modulation techniques used to produce and detect squeezed beams.

The detector is based on an offset Sagnac interferometer with modulation. In this interferometer, the local oscillator beam passes around the atoms, minimizing the destruction of the measurement. The low frequency technical noise, or geometrical noise, caused by mirror vibrations that commonly plagues separated path interferometers is avoided with two layers of passive noise suppression. The first layer is a result of the geometry of the offset Sagnac. To first order, a perfectly aligned Sagnac is immune to geometrical noise as both beams travel the same path in opposite directions. The offset Sagnac retains some of this immunity. The second layer, arising from carefully designed modulation and detection, is applicable to any interferometer used to detect a resonant system such as a cold atomic sample.

The spontaneous emission rate in a density measurement of cold atoms in a MOT with a probe detuning of 70 MHz, was calculated to be 4 photons/atom/sec. This is the least destructive measurement on cold atoms to date using a detector that is suitable for probing fast dynamics and is compatible with feedback and squeezing.

References

[1] F. Dalfovo *et al.*, **71**, 463 (1999); A. J. Leggett, **73**, 307 (2001); M. H. Anderson *et al.*, Science **269**, 198 (1995); K. B. Davis *et al.*, **75**, 3969(1995); C. C. Bradley, C. A. Sackett, J. J. Tollett, and R. G. Hulet, **75**, 1687 (1995).
[2] J. E. Lye, J. J. Hope, and J. D. Close, Phys. Rev. A. **67** 043609 (2003).
[3] J. J. Hope and J.D. Close, quant-ph/0308153.
[4] M. R. Andrews *et al.*, Science **273**, 84-87 (1996)
[5] S. Kadlecek, J. Sebby, R. Newell, and T. G. Walker, Opt. Lett. **26**, 137 - 139(2001).
[6] C. C. Bradley , C. A. Sackett, and R. G. Hulet , Phys. Rev. Lett. **78**, 985 - 989 (1997).
[7] J. E. Lye, J. J. Hope and J. D. Close, accepted for publication in Phys. Rev A.

Thermal simulations of Bose-Einstein condensates

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The Gross-Pitaevskii equation (GPE) has proven to be an extremely useful description of macroscopic Bose-Einstein condensates (BECs) at or near zero temperature [1]. However, it has been suggested that it can also be a useful description of Bose gases at finite temperatures [2]. This project aims at the quantitative implementation of a computational method based on classical fields to simulate BECs in the presence of a significant fraction of thermal atoms. While necessarily being an approximate scheme, it is targeted at performing calculations for realistic experimental systems. It is directly relevant to the ACQAO pumped cw atom laser effort, as any pumping involving evaporative cooling will necessarily be performed at finite temperature. There have been three major advances in this simulation technique for three dimensional BECs in 2003.

The first achievement has been the development of a non-perturbative method for determining the temperature of simulations once equilibrium has been reached. This makes use of microcanonical statistical mechanics applied to the classical field BEC Hamiltonian. This technique has resulted in a measure of the shift of the transition temperature for BEC for the homogeneous gas, a topic of some controversy in recent years [3]. Our result agrees with sophistated Monte-Carlo calculations of lattice field theory [4], and the specific heats of the system have also been determined [5].

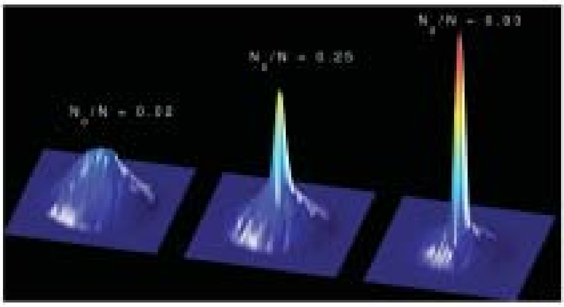

Figure 1: Time-averaged momentum space column densities of trapped Bose gases

The second advance is the application of the simulation method to the more experimentally relevant trapped gas Hamiltonian. Previous calculations have been performed for the homogeneous gas only due to the technical difficulty of implementing a mode cut-off for a three-dimensional harmonic oscillator. However, these have been overcome by making use of an efficient numerical quadrature, and performing simulations in the harmonic oscillator basis. Calculations using this new code base have begun recently, and the results compared with a recent experiment performed at ENS in Paris on the shift of the transition temperature.

A difficulty with the simulation method has been in treating the interaction of particles above the cutoff with the classical field representing the condensate plus excitations. The final major development for 2003 has been the derivation of the equations of motion with the above cutoff atoms behaving as a bath, with a local temperature and chemical potential. This results in noise and damping terms in the classical field equation, and this has been termed the stochastic Gross-Pitaevskii equation [6]. This will be useful in calculations of, for example, condensate growth.

References

[1] F. Dalfovo, S. Giorgini, L. P. Pitaevskii and S. Stringari, Rev. Mod. Phys. **71**, 463 (1999).

[2] B. V. Svistunov, J. Moscow Phys. Soc. **1**, 373 (1991); Yu. Kagan, B. V. Svistunov, and G. V. Shlyapnikov, Zh. Eksp. Teor. Fiz. **101**, 528 (1992) [Sov. Phys. JETP **75**, 387 (1992)].

[3] P. Arnold and G. D. Moore, Phys. Rev. E **64**, 066113 (2001), and references within.

[4] P. Arnold and G. Moore, Phys. Rev. Lett. **87**, 120401 (2001). V. A. Kashurnikov *et al.*, *ibid.*, 120402 (2001).

[5] M. J. Davis and S. A. Morgan, Phys. Rev. A **68**, 053615 (2003).

[6] C. W. Gardiner and M. J. Davis, J. Phys. B **36**, 4731 (2003).

Quantum correlations and coherence of a one-dimensional Bose gas

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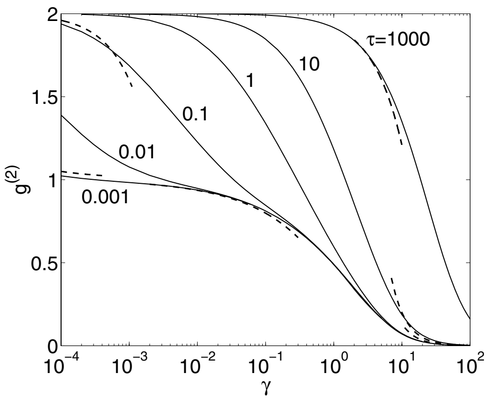
The interacting one-dimensional (1D) Bose gas model is a system of much theoretical interest that is now able to be realized experimentally. This raises the possibility of investigating the famous transition to fermionic behaviour that is predicted to occur at low density and strong inter-atomic interaction [1, 2].

We have calculated the two-particle local correlation function for an interacting one-dimensional Bose gas at finite temperature [3]. Remarkably, the calculation is performed exactly, using the numerical solution of the Yang-Yang equations derived in the 1960s [4]. This means that the results obtained go far beyond the commonly used approximations of the mean-field and Bogoliubov theories valid only for weak interaction strengths.



The figure on the left shows the local pair correlation $g^{(2)}$ of an interacting 1D Bose gas as a function of the interaction strength parameter γ, for different (dimensionless) temperatures $\tau = T/T_d$, where T_d is the temperature of quantum degeneracy. We find that the pair correlation is a sensitive measure for identifying and classifying various regimes of quantum degeneracy of 1D Bose gases. This includes both the regime of coherent output of an atom laser operating in a 1D environment (such as atom-chip devices), and that of finite-temperature "fermionization".

The later regime (not encountered in 3D Bose gases) is characteristic of strong inter-particle interactions or low particle densities, and until recently its achievement was one of the major experimental challenges in the field. In December 2003, the Nobel prize-winning research group of Professor W. Phillips at the US National Institute of Standards and Technology, reported experimental verification of the theoretical work carried out at the University of Queensland, ACQAO, in collaboration with G. V. Shlyapnikov and D. M. Gangardt.

Our studies of pair correlations have also been extended to the case of non-uniform (trapped) 1D Bose gases. This is more relevant to laboratory experiments, allowing for direct comparison with our theoretical predictions.

We have also carried out canonical Bose gas simulations using stochastic gauge techniques and calculated the non-local pair correlation for the 1D Bose gas problem [6]. This work further extends our understanding of higher-order correlations and the quantum statistics of 1D Bose gases, as well as provides a novel technique for numerical studies of quantum many-body systems for situations in which analytical approaches do not exist.

References

[1] M. D. Girardeau, J. Math. Phys. **1**, 516 (1960); Phys. Rev. **139**, B500 (1965).
[2] E. H. Lieb and W. Liniger, Phys. Rev. **130**, 1605 (1963); E. H. Lieb, *ibid.* 1616 (1963).
[3] K. V. Kheruntsyan, D. M. Gangardt, P. D. Drummond, G. V. Shlyapnikov, Phys. Rev. Lett. **91**, 040403 (2003).
[4] C. N. Yang and C. P. Yang, J. Math. Phys. **10**, 1115 (1969).
[5] B. Laburthe *et. al.*, arXiv: cond-mat/0312003.
[6] P. D. Drummond, P. Deuar, and K. V. Kheruntsyan. arXiv: cond-mat/0308219 (to appear in Phys. Rev. Lett.).

Understanding the Bosenova

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We solved the cylindrically symmetric Gross-Pitaevskii equation numerically for BEC collapse induced by a switch from positive to negative scattering lengths [1]. We compared our results with experiments performed at JILA with Bose-Einstein condensates of ^{85}Rb, in which the scattering length was controlled using a Feshbach resonance [2]. Building on previous theoretical work we identifed quantitative differences between the predictions of mean-field theory and the results of the experiments. Besides the previously reported difference between the predicted and observed critical atom number for collapse, we also found that the predicted collapse times systematically exceeded those observed experimentally (see figure).

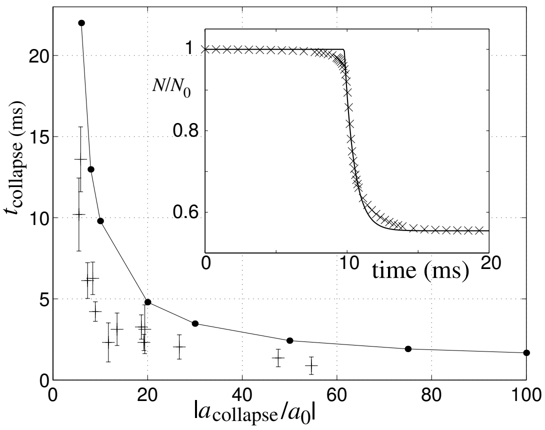

Figure: Experimental and numerical results for the collapse time t_{collapse} versus scattering length a_{collapse} after a switch from $a = 0$ to a_{collapse}. The experimental points (+) and their error bars are from Fig. 2 of Donley *et al.* [2]. Inset: Example of the fitting procedure used to determine the collapse times. Shown is a fit of the functional form $N = (N_0 - N_{\text{f}})\exp[-(t - t_{\text{collapse}})/\tau_{\text{decay}}] + N_{\text{f}}$ (solid line) to the GP simulation ($\times$) for $a = -10a_0$. The fit parameters here are $t_{\text{collapse}} = 9.8$ ms, $\tau_{\text{decay}} = 0.7$ ms, and $N_{\text{f}}/N_0 = 0.5544$.

There is a significant theoretical literature on the bosenova, most of which appears to regard the fit shown in the figure as adequate. However, some workers have suggested that quantum corrections to the mean field model are required to fully understand the bosenova experiment [3].

We are investigating this hypothesis by extending our numerical model to the time dependent Hartee-Fock-Bogolubov approximation [4], with an auxillary molecular condensate field [5]. This approximation includes the non-condensed part of the atomic field $\hat{\chi}(\mathbf{r})$ using the single particle density matrix $\langle\hat{\chi}^\dagger(\mathbf{r})\hat{\chi}(\mathbf{r}')\rangle$, and the anomalous density $\langle\hat{\chi}(\mathbf{r})\hat{\chi}(\mathbf{r}')\rangle$. The mean field of the non-condensed atoms is twice that of the condensed atoms, hence they should accelerate the collapse, as required.

The spherically symmetric case has already been considered by Milstein *et al.* [5]. The cylindrically symmetric case will be numerically challenging as the density matrix and anomalous density are five dimensional. The National Facility of the Australian Partnership for Advanced Computing will be used to tackle this problem [6].

References

[1] C. M. Savage, N. P. Robins and J. J. Hope, Phys. Rev. A **67**, 014304 (2003).
[2] E. A. Donley, N. R. Claussen, S. L. Cornish, J. L. Roberts, E. .A. Cornell and C .E. Wieman, Nature **412**, 295 (2001).
[3] E. A. Calzetta and B. L. Hu, Phys. Rev. A **68**, 043625 (2003).
[4] J.-P. Blaziot and G. Ripka, *Quantum theory of finite systems* (The MIT Press, Cambridge, 1986).
[5] J. N. Milstein, C. Menotti, and M. J. Holland, New J. Phys. **5**, 52.1 (2003).
[6] Details of the National Faciltity may be found at: http://nf.apac.edu.au/

Skyrmions, monopoles, and dipoles in BECs

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We have numerically simulated topological defects in multi-component atomic BECs. Examples of topological defects include vortices in single component fields, and the structures we have investigated in multi-component fields: skyrmions, monopoles, and dipoles. Defects characterized by a topologically invariant winding number are important in the study of superfluids, cosmology, and sub-atomic physics. A skyrmion model predicted the recently observed five-quark baryons [1].

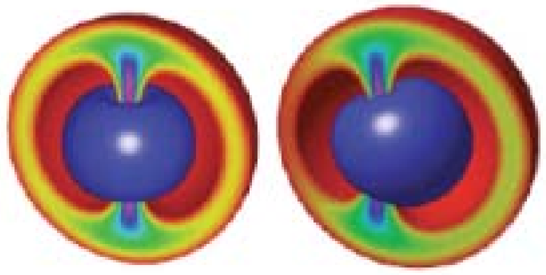
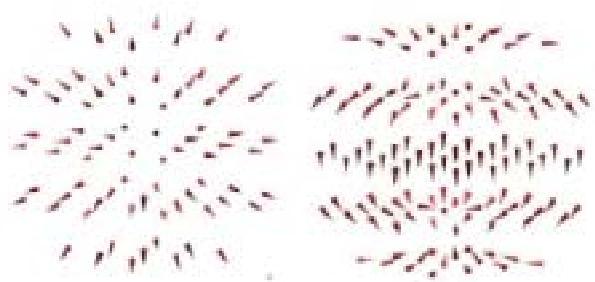


Figure: 3D density profiles of energetically stable trapped skyrmions. The central torii are isosurfaces of the atomic state forming a line vortex. The other atomic state forms a ring vortex: isosurfaces are shown for $x < 0$. On the $y-z$ plane between the isosurface sections, density is indicated by a colormap. Left: Stabilized by rotating the line vortex component only. Right: Stabilized by rotating the entire system.

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 identified, and showed how to overcome, the specific instabilities of skyrmions in trapped two-species atomic BECs, and hence demonstrated numerically their energetic stability under realistic experimental conditions [2]. 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 rotation, or by a laser potential.

We also investigated topological structures in an optically trapped spin-1 BEC: the Dirac monopole, which has a hedgehog-like structure of radial spin vectors, and the dipole, which is a monopole-anti-monopole pair joined by a vortex. We numerically simulated the three dimensional dynamics and imaginary time relaxation of these structures for realistic experimental parameters. The figure shows spin fields for a monopole (left) and a dipole (right).



The monopole has a vortex line with a free end, terminating on a spin configuration whose superfluid velocity profile coincides with the vector potential of the Dirac magnetic monopole. In the dipole the vortex joins the monopole and anti-monopole, such that neither end reaches the BEC boundary. The National Facility of the Australian Partnership for Advanced Computing was used for this work [4].

References

[1] C. Day, Physics Today, page 19 September (2003).
[2] C. M. Savage and J. Ruostekoski, Phys. Rev. Lett. **91**, 010403 (2003).
[3] C. M. Savage and J. Ruostekoski, Phys. Rev. A **68**, 043604 (2003).
[4] Details of the National Faciltity may be found at: http://nf.apac.edu.au/

Gaussian quantum phase-space methods

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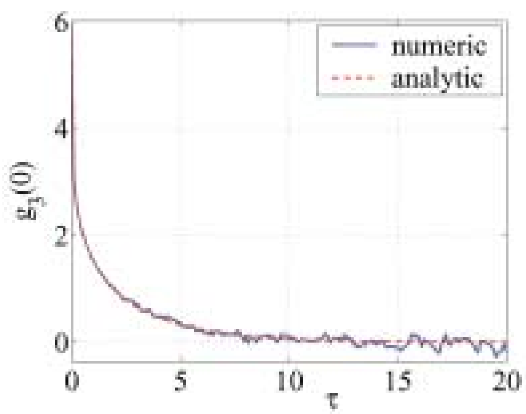
The physics of quantum, many-body systems underlies the whole ACQAO research program, and tractable methods to simulate this physics is the goal of the research stream in quantum phase-space methods. The methods are based on techniques that were originally developed in quantum optics and are now being tailored to systems of massive particles (atoms). Strategically, the research is being pursued in three complementary directions[1]: 1) alternative bases for operator expansion, 2) stochastic gauges and 3) sampling methods.

Of the three research strategies, the most radical developments are wrought through changing the basis: 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 states of the system being studied, leading to greater efficiency in the stochastic sampling.



Third-order correlation function versus (scaled) inverse temperature, for Mott insulator bosons

In 2003, we developed a generalised set of methods based on a Gaussian operator expansion[2]. The Gaussian methods incorporate and generalise all previously used phase-space methods, and also include in the basis thermal and squeezed states, which are relevant to the physics of Bose-Einstein condensates. Unlike previous (coherent-state-based) methods, any linear (single-particle) problem maps onto a set of deterministic, linear phase-space equations. Additionally, many nonlinear problems (including any problem with two-body interactions) map onto a set of stochastic equations, which can be simulated numerically. We have applied the Gaussian methods to some simple many-body systems (eg atoms in a small lattice), and in particular to calculations of equilibrium states, to confirm that the new methods produce the expected results (see figure).

The development of the Gaussian methods also requires the development of new stochastic gauges. The mapping from quantum operator equations to the stochastic equations allows a freedom for 'gauge' functions to be included. These functions do not affect the ensemble-average physics, but can improve the stability of the simulations. Gauges are a necessary feature for simulating underdamped systems of interacting particles, which is the typical situation in BEC. Recent work has used gauges to enable exact calculations of the equilibrium states of a 1D Bose condensate[3]. We also developed gauges to stabilise the Gaussian simulations of interacting particles in a lattice.

The structure of the Gaussian expansion is such that it can naturally adapted to treat *fermionic* systems. The ground-work and formalism for the fermion case has been developed and has been applied to calculations of equilibrium states and dynamics in some simple lattice problems.

References

[1] P. D. Drummond, P. Deuar, J. F. Corney and K. V. Kheruntsyan, in Proceedings of the 16th International Conference on Laser Spectroscopy (to appear), *cond-mat/0309537*.
[2] J. F. Corney and P. D. Drummond, Phys. Rev. A **68**, 063822 (2003), *quant-ph/0308064*.
[3] P. D. Drummond, P. Deuar and K. V. Kheruntsyan, Phys. Rev. Lett. **92**, 040405 (2004), *cond-mat/0308219*.

The Metropolis algorithm for real time quantum dynamics

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This work has concentrated on developing new computational algorithms for quantum dynamics in generalised phase spaces. The gauge-P representation [1] generates an infinite class of stochastic differential equations equivalent to the quantum master equation, for which quantum dynamical expectation values are obtained by calculating averages over many stochastic trajectories. A feature of these is, that unlike the more familiar positive-P representation, each trajectory is accompanied by a weighting factor. This suggests the possibility of treating the weight as a probability and utilising techniques from Monte Carlo calculations in order to efficiently sample the stochastic trajectories. We have applied the well-known Metropolis-Hastings algorithm [2] to the problem in order to sample the high-weight trajectories in an unbiased manner.

The method requires that real gauge functions be used so that the weights are real and can be properly interpreted as probabilities. This restricts the gauge freedom somewhat, however we have successfully observed up to a five-fold decrease in sampling error for some calculations when compared to ordinary stochastic sampling. We have concentrated on the single-mode Kerr anharmonic oscillator with Hamiltonian $H = \kappa(\hat{a}^\dagger)^2\hat{a}^2$, which can represent a single well of a Bose gas in an optical lattice. In the future we hope that improved candidate generating functions will lead to further gains in efficiency.

References

[1] P. Deuar and P. D. Drummond, Phys. Rev. A **66**, 033812 (2002).
[2] S. Chib and E. Greenberg, The American Statistician **49**, 327 (1995).

Pairing transition of the attractive Bose gas

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The possibility of a pairing phase transition in a Bose gas with a partly attractive interactions ("BCS for bosons") was first considered by Evans and Imry [1]. However, later calculations concluded that boson pairing was not the cause of superfluidity in helium-4 below the lambda point [2]. The possibility of pairing was considered for atomic alkali gases in [3], and while the transition temperature for pairing was found to be higher than that for BEC, it was still below the temperature at which the gas would undergo mechanical collapse. It was thought that BEC was not possible for gases with attractive interactions, however this is only true in the thermodynamic limit. For finite systems it is now known that condensation can occur for a limited number of atoms [4]. The possibility of a pairing transition for bosons in a finite system has yet to be properly considered.

We have performed calculations for a finite-sized uniform Bose gas with attractive interactions within the Hartree-Fock-Bogoliubov formalism. We have found solutions for which the anomalous average $\tilde{m} = \langle\hat{\Psi}\hat{\Psi}\rangle$ is macroscopic while the population of the ground state is not, and these occur in an experimentally accessible parameter regime. We are currently determining the stability of these solutions, and calculating other system properties such as the spectrum of collective excitations.

References

[1] W. A. B. Evans and Y. Imry, Il Nuovo Cimento **63B**, 155 (1969).
[2] P. Dörre, H. Haug, and D. B. Tran Thoai, J. Low Temp. Phys. **35**, 465 (1979).
[3] H. T. C. Stoof, Phys. Rev. A, **49**, 3824 (1994).
[4] C. C. Bradley, C. A. Sackett, J. J. Tollet and R. Hulet, Phys. Rev. Lett. **79**, 1170 (1997).

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.

This year has been spent constructing a state-of-the-art metastable helium beamline suitable for achieving BEC. We use a liquid helium cooled source of He* atoms [2] which produces a beam with a most probable velocity $\sim$ 700 ms^{-1}. He* atoms are collimated directly after the source by application of laser beams in two dimensions. This collimated beam of He* atoms is then slowed using a σ^- Zeeman slower. The highest flux obtained out of the source to date is $\sim 10^{14}$ /s.sr below 700 ms^{-1}, the capture velocity of our Zeeman slower (see figure 1). With a slowing intensity of approximately $26I_{sat}$, our Zeeman slower slows almost all atoms below 700 ms^{-1}, resulting in a slowed atomic beam $\sim 10^{10}$ He* atoms/s. Such a flux will allow efficient loading of a He* Magneto-optic trap (MOT), the first stage towards BEC of He*.

Figure 1: An image of the He* beamline. The Zeeman slower can be seen in the left of the image, while the MOT chamber is shown to the right. The source end of the beamline is not shown.

In the coming year we plan to load a large number of He* atoms into a MOT. These atoms will be transferred, via a low velocity intense source (LVIS) [3], to a second MOT located in a region of higher vacuum. Transfer from this MOT into a tightly confining magnetic trap and subsequent radio frequency evaporation should lead to condensation of He*. In parallel we will develop a high spatial and temporal resolution position sensitive detector for precise measurement of the interference pattern formed by the two He* BECs.

References

[1] T. Wong, M. J. Collet, and D. F. Walls , Phys. Rev. A **54**, R3718 (1996);
[2] J. A. Swansson, K. G. H. Baldwin, M. D. Hoogerland, A. G. Truscott, S. J. Buckman, *Appl. Phys. B.* (submitted for publication);
[3] Z. T. Lu, K. L. Corwin, M. J. Renn, M. H. Anderson, E. A. Cornell and C. E. Wieman , Phys. Rev. Lett. **77**, 3331 (1996);

Bose-Einstein Condensation on a Chip

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In the late 1990s our group developed and successfully tested two kinds of microfabricated atom optical elements that form planar structures on a substrate –"atom chips". Firstly, a silicon-based array of micro-electromagnets was fabricated by photolithography and used as a mirror for quantum-state-selective reflection of cold caesium atoms [1]. Secondly, grooved magnetic films with periods of 1 and 2 μm were used for near specular reflection of cold caesium and rubidium atoms [2, 3]. We have set up a project aimed at the production of Bose-Einstein condensed rubidium atoms on a chip and the construction of a coherent source of matter waves (on-chip atom laser). A new generation of atom chips will be based on this technology which will combine the use of current-carrying micro-wires and permanent magnetic microstructures [3]. Miniaturisation and scaling down the dimensions of atom traps can greatly simplify the production of a BEC. Large magnetic field gradients and curvatures can be obtained by using moderate electric currents or micromagnets with large values of remanent magnetisation.

In preliminary experiments we have tested the performance of an atom chip which was made from a U-shaped kapton-coated copper wire located beneath a gold-coated silicon wafer of area 20 x 20 mm^2. Rubidium atoms were cooled and trapped in a mirror-MOT formed by four laser beams and external quadrupole coils. The trapped atoms were then transferred to the mirror-MOT formed by the laser beams and a quadrupole magnetic field produced by the U-shaped wire carrying a current of 3 A and an external bias field of 2 G. We have studied the efficiency of the transfer of cold atoms and the time sequence of events.

A long-term aim of the project is the development of quantum atom gravity sensors through the integration of an on-chip atom laser with an atom interferometer. We are currently investigating a particular type of atom interferometer based on the splitting of a single-well potential into a double-well potential followed by recombination [4]. We are also developing a theory of decoherence of BECs due to thermal effects and the environment using the stochastic gauge formalism.

Cloud of cold rubidium atoms (temperature $\approx$ 25 μK) trapped in the mirror-MOT below the surface of the atom chip. The hot dispenser pictured on the right side produces a rubidium vapour for loading the trap.

References

[1] D. C. Lau, A. I. Sidorov, G. I. Opat, R. J. McLean, W. J. Rowlands, and P. Hannaford, Eur. Phys. J. D 5, 193 (1999).

[2] A. I. Sidorov, R. J. McLean, B. A. Sexton, D. S. Gough, T. J. Davis, A. Akulshin, G. I. Opat, and P. Hannaford, Comptes Rendus 2, Series IV, 565 (2001).

[3] A. I. Sidorov, R. J. McLean, F. Scharnberg, D. S. Gough, T. J. Davis, B. A. Sexton, G. I. Opat, and P. Hannaford, Acta Physica Polonica B 33, 2137 (2002).

[4] S. Whitlock, B. Dalton, F. Scharnberg, T. Kieu, P. Hannaford, and A. I. Sidorov, ACOLS03 Book of Abstracts, p.117 (2003).

Molecular Bose-Einstein Condensation

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The Swinburne University node of ACQAO is setting up an experimental project to produce a Bose-Einstein condensate (BEC) of molecules. This is an exciting and important extension of atomic Bose-Einstein condensation, which has potential application in the production of quantum entangled atomic beams.[1] This area of research has generated a good deal of interest in recent times, with the first observations of molecular BEC, based on fermionic atoms (^{6}Li and ^{40}K) from several groups occurring very recently within days of each other. [2] [3] [4]

The initial phase of the experiment, producing an atomic BEC, is currently underway. The atomic system used is caesium (Cs, a bosonic atom), which has only recently been demonstrated to undergo the BEC transition [5]. To avoid inelastic two-body losses, the lowest hyperfine ground state $F = 3$ $m_F = 3$ state is used, which is not magnetically trappable (i.e. it is high-field seeking). The trapping and evaporative cooling to BEC is therefore done in far off-resonant optical dipole traps (FORTs). In the absence of a magnetic field, Cs has a negative scattering length (i.e. attractive interaction). The sign and magnitude of this scattering length can be altered, however, by magnetically tuning across a Feshbach resonance. A relatively broad Feshbach resonance exists for Cs at a magnetic field of around 20 G, which can be used to give fine control over the scattering length during evaporation, and even tuned to zero-scattering length at 17 G, producing a non-interacting condensate.

To convert some fraction of the atomic BEC to molecules, a magnetic field sweeps across the Feshbach resonance. Although this association technique seems to provide reasonably efficient production of molecules from the atomic BEC, the molecules are created in vibrationally excited states, which will limit the lifetime of the molecular ensemble as this vibrational energy is released via collisions. Theoretical research is being carried out on processes for generating molecular BECs from atomic condensates, such as that involving a Feshbach resonance plus STIRAP (Stimulated Raman Adiabatic Passage) leading to a molecular condensate in the ground vibrational state, and hence closer to absolute zero in temperature. Ideally, the conversion process is coherent, but various decoherence processes such as spontaneous emission need to be need to be taken into account to be realistic. Also, quantum fluctuations around the condensate wavefunctions, occurring when the numbers of atoms or molecules is small, would be important. Accordingly, the stochastic gauge theory formalism is suitable for treating these issues, though a multi-component version to allow for both atomic and molecular condensates is required.

The present status of the project has the various component systems (vacuum, lasers, optics, magnetic coils, etc.) under construction.

References

[1] K. V. Kheruntsyan and P. D. Drummond, Phys. Rev. A **66**, 031602(R) (2002)
[2] M. Greiner, C. A. Regal, and D. S. Jin, preprint cond-mat/0309078
[3] S. Jochim, M. Bartenstein, A. Altmeyer, G. Hendl, S. Reidl, C. Chin, J. Hecker Denschlag and R. Grimm, Science Express, 13 November 2003
[4] M. W. Zwierlein, C. A. Stan, C. H. Schunck, S. M. F. Raupach, S. Gupta, Z. Hadzibabic and W. Ketterle, preprint cond-mat/0311617
[5] T. Weber, J. Herbig, M. Mark, H.-C. Nagerl and R. Grimm, Science. **299**, 232 (2003).

Molecule formation from quantum Bose and Fermi gases

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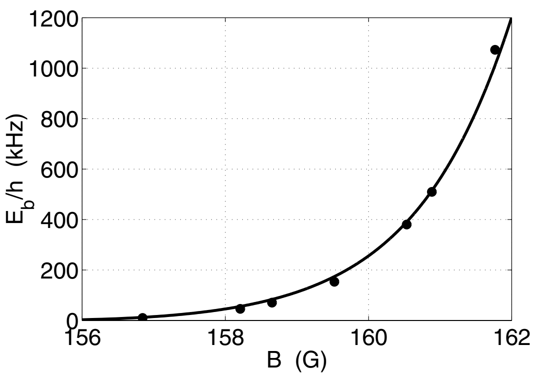
The application of magnetic field pulses to a cold atomic gas in the vicinity of a Feshbach resonance has enabled a fascinating new probe of quantum dynamical behaviour in coupled atom-molecular systems, together with remarkably precise measurements of quantum binding energies. The first step towards seeing molecular condensation was recently undertaken in transient experiments with a Bose-Einstein condensate (BEC) of ^{85}Rb atoms [1], in which interference measurements were indicative of molecular BEC formation. More recent experiments with ^{133}Cs and ^{87}Rb [2], as well as with degenerate Fermi gases of ^{40}K and ^{6}Li atoms [3], have produced an even larger fraction of ultra-cold molecules as well as BECs of bosonic molecular dimers composed of fermionic atoms.

In this work, we have revisited the effective quantum field theory [4, 5] as a generic model of molecule formation from pairs of atoms in a Bose-Einstein condensate or in a degenerate Fermi gas of atoms near a Feshbach resonance. This point-contact model theory can be renormalized exactly and non-perturbatively [6]. It also has an exact analytic solution for the two-particle ground state [4, 5], describing bosonic ”dressed” molecules consisting of either bosonic or fermionic atom pairs. The ground state is a coherent quantum superposition of a ”bare” molecule with a pair of atoms.



We have calculated [7] the binding energies E_b of the molecular dimers as a function of the applied magnetic field strength B, and the results are in remarkable agreement with the inferred binding energies observed in [1] (see figure). The solid line is our theoretical result, while the circles are the experimental data. Good agreement with the measured binding energies is also found for the cases involving fermionic atoms, thus verifying our original model, which is now used by many groups.

The exact solubility of this simple yet universal field-theoretic model means that one can obtain analytic expressions for a range of relevant quantities, including the binding energy and the resulting fraction of molecules. Our conclusion is that the use of field theoretic models can allow a quantitative picture of quantum many-body effects in Feshbach molecule formation experiments without requiring a detailed molecular calculation for each specific molecule.

We have also completed an investigation into three-dimensional (3D) matter-wave soliton formation in a coherently coupled atom-molecular BEC. The work is mostly numerical using mean-field techniques, and indicates that stable 3D solitons are possible, unlike for a single component BEC.

References

[1] E. A. Donley *et al.*, Nature **417**, 529 (2002).
[2] J. Herbig *et al.*, Science **301**, 1510 (2003); S. Dürr *et al.*, cond-mat/0307440.
[3] C. A. Regal *et al.*, Nature **424**, 47 (2003); M. Greiner *et al.*, *ibid.* **426**, 537 (2003); K. J. Cubizolles *et al.*, Phys. Rev. Lett. **91**, 240401 (2003); K. E. Strecker *et al.*, *ibid.* **91**, 080406 (2003); M. W. Zweirlein *et al.*, *ibid.* **91**, 250401 (2003).
[4] P. D. Drummond, K. V. Kheruntsyan, and H. He, Phys. Rev. Lett. **81**, 3055 (1998).
[5] K. V. Kheruntsyan and P. D. Drummond, Phys. Rev. A **61**, 063816 (2000).
[6] S. J. J. M. F. Kokkelmans and M. J. Holland, Phys. Rev. Lett. **18**, 180401 (2002).
[7] P. D. Drummond and K. V. Kheruntsyan, Bull. Am. Phys. Soc. **48**, No. 3, 68 (2003); APS DAMOP 2003 Annual Meeting, Boulder, Colorado, USA (May 20-24, 2003).

Bose-Einstein condensates in optical lattices

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Bose-Einstein condensates in optical lattices form band-gap structures with high degree of control over their parameters. An optical lattice potential modifies diffraction properties of the intrinsically nonlinear matter waves which can lead to nonlinear localization of a BEC in the form of bright solitons embedded into the spectral gaps. Similarly, dark solitons can form on the Bloch-wave background within the spectral bands. During this year we analyzed nonlinear localization of single and multiple-component BECs in 1D and 2D optical lattices, and initiated work on optical superlattices. The results obtained so far lay a background for further studies of the stability, mobility, and interactions of localized states. Our inspiration comes from the similarities between the physics of coherent light and matter waves. Diffraction management, localization, and manipulation of light in periodic photonic structures has revolutionized the modern photonics and enabled development of novel intergated photonic devices. We believe that optical lattices can provide similar opportunities for control and manipulation of coherent matter waves.

1D band-gap structures [1]: By analyzing the full continuous Gross-Pitaevskii model of a strongly elongated BEC cloud in a 1D lattice potential, we have found that nonlinear localization of BEC in the form of bright *gap solitons* occurs in all gaps of the multiple-band-gap structure imposed by the lattice. This type of localization is due to the balance of the effective nonlinearity of the matter wave (which depends on the type of the s-wave atomic interactions) and effective diffraction (which depends on the band curvature for a given momentum of the wavepacket), and can occur both for attractive and repulsive BECs. A weak instability of such localized states has been attributed to resonance of the internal modes of the excitation spectrum with the linear Bloch-wave bands.

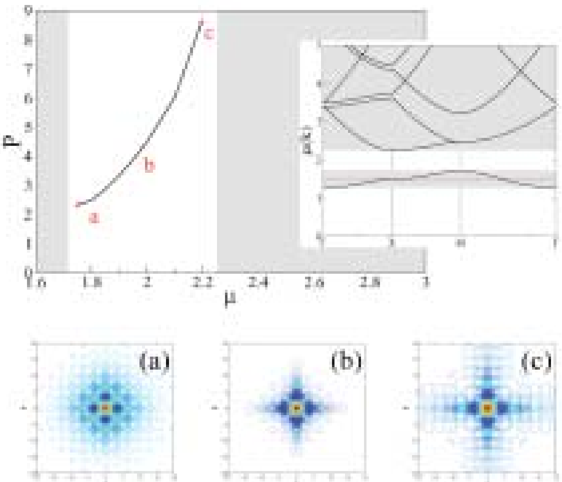

Figure 1: Norm, $P = \int |\psi|^2 d\vec{r}$, vs. chemical potential, μ, of the atomic soliton wavefunction $\psi(x, y)$ (a,b,c) in the complete gap of a 2D square optical lattice. Inset: Bloch-wave bands $\mu(k)$ (shaded) for the same optical lattice (dotted line shows potential depth), plotted along high-symmetry lines of the first Brillouine zone.

2D band-gap structures [2]: Localization of BEC in higher spatial dimensions becomes anisotropic. For an repulsive BEC in a 2D lattice, presence of both a complete gap (Fig. 1, inset) and the anomalous components of the dispersion tensor is required in order for the soliton to be localized in all directions [see Fig. 1 (b)]. We have adopted a reliable numerical technique for analysing the spatial and phase structure of fundamental and higher-order localized states.

Nontrivial phase states [3]: Together with our collaborators, we investigated novel states with nontrivial phase in BEC - ring dark solitons. We showed that relatively shallow rings are not subject to the snake instability, but a deeper ring splits into a robust ringlike cluster of vortex pairs, which performs oscillations in the radial and azimuthal directions, following the dynamics of the original ring soliton. The on-going continuation of this work includes investigation of ring vortex trapping and stabilization in a 2D optical lattice.

References

[1] P. J. L. Louis, E. A. Ostrovskaya, C. M. Savage, and Yu. S. Kivshar, Phys. Rev. A **67**, 013602 (2003).
[2] E. A. Ostrovskaya and Yu. S. Kivshar, Phys. Rev. Lett. **90**, 160407 (2003).
[3] G. Theocharis, D. J. Frantzeskakis, P. G. Kevrekidis, B. A. Malomed, and Yu. S. Kivshar, Phys. Rev. Lett. **90**, 120403 (2003).

Macroscopic quantum entanglement and quantum squeezing

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Work has commenced on the development of entanglement signatures with particular focus on the signatures of macroscopic entanglement. Criteria for detecting entanglement, using signatures associated with the proof of the existence of EPR correlations for continuous variables, have been extended to provide entanglement criteria for the situation of macroscopic superpositions of coherent states[1, 2, 3]. A further paper, in preparation, examines how to extend EPR-entanglement criteria to prove the existence of quantum superpositions of macroscopically-distinct states in a Pointer basis- that is, to prove the existence of appropriate nonzero off-diagonal terms in the quantum density matrix. Such criteria could potentially be used to deduce macroscopic superpositions in simple squeezed light fields currently generated. In relation to this, a program is in progress to develop modified Bell-type inequalities, the violation of which would indicate a failure of macroscopic realism and thus provide a strong ”nonquantum” signature of the macroscopic paradox of the ”Schroedinger cat”. A parallel investigation is developing macroscopic-entanglement criteria for correlated higher-spin systems using new signatures sufficient to prove the Bohm version of the EPR paradox, with the objective being to study ”Schroedinger cats” in atom-light systems.

As a practical application of these ideas, we have carried out a complete, fully quantum mechanical treatment of the nondegenerate optical parametric oscillator both below and near threshold[4]. This is a non-equilibrium quantum system with a critical point phase-transition, that is also known to exhibit strong yet easily observed squeezing and quantum entanglement. Our treatment makes use of the positive P-representation and goes beyond the usual linearized theory. We compare our analytical results with numerical simulations and find excellent agreement. We also carry out a detailed comparison of our results with those obtained from stochastic electrodynamics, a theory obtained by truncating the equation of motion for the Wigner function, with a view to locating regions of agreement and disagreement between the two. We calculate measures of quantum behavior including entanglement, squeezing and EPR correlations as well as higher order tripartite correlations, and show how these are modified as the critical point is approached. In general, the critical fluctuations represent an ultimate limit to the possible entanglement that can be achieved in a nondegenerate parametric oscillator.

Further results[5] and a general review of the field of quantum squeezing and entanglement are now published[6] in a new book entitled **Quantum Squeezing**.

References

[1] M.D. Reid, *Einstein-Podolsky-Rosen Correlations, Entanglement and Quantum Cryptography* in Quantum Squeezing, p337-358, P. D. Drummond and Z. Ficek (eds) (Springer, Berlin, 2003).

[2] M. D. Reid, *Signatures of Schroedinger cat paradoxes and macroscopic entangled states*, contributed talk, International Workshop on Bose-Einstein Condensation and Quantum Information (BECQI03), Caloundra, Australia, (Feb 2003).

[3] M. D. Reid, *The Einstein-Podolsky-Rosen Paradox and Entanglement: Signatures of EPR Correlations for Continuous Variables*, (submitted to PRA).

[4] K. Dechoum, P. D. Drummond, S. Chaturvedi and M. D. Reid, *Critical fluctuations and entanglement in the nondegenerate parametric oscillator*, quant-ph/0310129 , (submitted to PRA).

[5] P. D. Drummond, *Squeezing with Nonlinear Optics* in Quantum Squeezing, p99-140, P. D. Drummond and Z. Ficek (eds) (Springer, Berlin, 2003).

[6] P. D. Drummond and Z. Ficek (Eds) Quantum Squeezing (Springer, Berlin, 2003).

Software development

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Software development at the UQ node revolves around furthering the capabilities of XMDS—the eXtensible Multi-Dimensional Simulator [1]. The addition of new features, documentation of the code and the program itself, adding a new configuration mechanism, and doing general testing has been carried out over the last four months by Paul Cochrane. Over this time XMDS has been steadily improving, currently being at version 1.2 of the program. In addition, we are planning a longer-term development leading to a version 2.0, which will have a more powerful library and kernel structure, and a license suitable for commercialization.

There have been many fundamental improvements to XMDS including:

- The use of the GNU suite of software development tools for automatic configuration of XMDS for any sufficiently UNIX-like platform.
- Binary input and output of data files.
- Improved use of the FFTW [2] feature set (including the use of ”wisdom”).
- A Matlab [3] function for the importing of binary and ascii simulation output data for graphical and other analysis.
- Documentation of the application-programmer interface for writing the internals of XMDS itself.
- Addition to, and improvement upon, documentation of the XMDS language/tag-set.
- Command line arguments using the GNU getopt functions in XMDS simulations.
- Addition of extra features (such as optimisation settings etc.) for building of simulation programs.
- User-defined preferences for building of simulations.
- Testing of software on a variety of platforms with the use of the Sourceforge [4] compile farm.

Although much work has been completed (and is still ongoing) there is still quite a wish list of functionality to be added to XMDS, such features include:

- Break points.
- Timed output.
- Moment groups in dynamics.
- Adaptive step size algorithms.
- Addition of other algorithms.
- Optimisation of output XMDS code.
- Development of a front end.
- Development of a test suite (this has been started).

More fundamental to XMDS is a proposed update to the XMDS language itself. Currently XMDS isn't as flexible as would be desired, and it is desired to rework the language itself, to make it more general, flexible and (hopefully) more intuitive to use. As well as this, the internals of XMDS are difficult to maintain in their current form and it has been proposed to recode XMDS in a language more suited to fast development and the processing of XMDS code into C language code.

Overall, XMDS proves to be a powerful tool with which to simply and quickly develop physics and mathematics simulations in a more error-free manner than using traditional techniques. Coupled with this and the proposed changes and feature improvements XMDS can only get better.

References

[1] `http://www.xmds.org`
[2] `http://www.fftw.org`
[3] `http://www.mathworks.com`
[4] `http://sourceforge.net`

PUBLICATIONS

BOOKS

1. H-A. Bachor and T.C. Ralph, A Guide to Experiments in Quantum Optics, 2nd Expanded Edition (VCH Wiley, 2003).

2. P.D. Drummond and Z. Ficek (Eds), Quantum Squeezing, (Springer, Berlin, 2003).

JOURNAL ARTICLES

3 A.M. Akulshin, A. Cimmino, A.I. Sidorov, P. Hannaford and G.I. Opat, 'Light Propagation in an Atomic Medium with Steep and Sign-reversible Dispersion', Phys. Rev. A 67, 011801 (2003).

4. A.M. Akulshin, A. Cimmino, A.I. Sidorov, R.J. McLean and P. Hannaford, 'Highly Nonlinear Atomic Medium with Steep and Sign-reversible Dispersion', J. Opt B: Quantum and Semiclassical Opt. 5, S479–S485 (2003).

5. U.L. Andersen, B.C. Buchler, P.K. Lam, Jinwei Wu, J.R. Gao and H-A. Bachor, 'Four Modes of Optical Parametric Operation for Squeezed State Generation', Eurr. Physi. J. D27, 181 (2003).

6. A.S. Bradley, J.J. Hope and M.J. Collett, 'Steady-State Quantum Statistics of a Non-Markovian Atom Laser II', Phys. Rev. A 68, 063611(2003).

7. J.F. Corney and P.D. Drummond, 'Gaussian Quantum Operator Representation for Bosons, Phys. Rev. A 68, 063822 (2003).

8. B.J. Dalton and B.M. Garraway, 'Non-Markovian Decay of a Three-Level Cascade Atom in a Structured Reservoir', Phys. Rev. A 68, 033809 (1–13) (2003).

9. M.J. Davis and S.A. Morgan, 'Microcanonical Temperature for a Classical Field: Application to Bose-Einstein Condensation', Phys. Rev. A 68, 053615 (2003).

10. P.D. Drummond and P. Deuar, 'Quantum Dynamics with Stochastic Gauge Simulations', J. Opt. B: Quantum Semiclass. Opt. 5, S281–S289 (2003).

11. C. Fabre, U. Andersen, H-A. Bachor, B. Buchler, S. Gigan, P.K. Lam, A. Maitre and N. Treps, 'Quantum Information Processing in Optical Images', Superlattices and Microstructures 32, 323 (2003).

12 C.W. Gardiner and M.J. Davis, 'The Stochastic Gross-Pitaevskii Equation: II', J. Phys. B 36, 4731–4753 (2003).

13. S.A. Haine and J.J. Hope, 'Mode Selectivity and Stability of Continuously Pumped Atom Lasers', Phys. Rev. A 68, 023607 (2003).

14**. K.V. Kheruntsyan, D.M. Gangardt, P.D. Drummond and G.V. Shlyapnikov, 'Pair Correlations in a Finite-Temperature 1D Bose Gas', Phys. Rev. Lett. 91, 040403 (2003).

15. P.J.Y. Louis, E.A. Ostrovskaya, C.M. Savage and Yu.S. Kivshar, 'Bose-Einstein Condensates in Optical Lattices: Band-gap Structure and Solitons', Phys. Rev. A 67, 013602 (2003).

16. J.E. Lye, J.J. Hope and J.D. Close, 'Non Destructive Dynamic Detectors for Bose-Einstein Condensates, Phys. Rev. A 67, 043609 (2003).

17.** E.A. Ostrovskaya and Yu.S. Kivshar, 'Matter-Wave Gap Solitons in Atomic Band-Gap Structures', Phys Rev. Lett. 90, 160407 (2003).

18. N. P. Robins, J. E. Lye, C. S.Fletcher, S Haine, C. M . Savage, J.J. Hope and J. D. Close, *Classical noise and flux: the Limits of Multi-state atom Lasers*, invited paper in the proceedings of the International Conference on Lasers and Spectroscopy, Palm Cove (2003).

19. C.M. Savage, N.P. Robins and J.J. Hope, 'Bose-Einstein Condensate Collapse: A Comparison Between Theory and Experiment', Phys. Rev. A 67, 014304 (2003).

20. C.M. Savage and J. Ruostekoski, 'Dirac Monopoles and Dipoles in Ferromagnetic Spinor Bose-Einstein Condensates', Phys. Rev. A 68, 043604 (2003).

21.** C.M. Savage and J. Ruostekoski, 'Energetically Stable Particle-Like Skyrmions in a Trapped Bose-Einstein Condensate', Phys. Rev. Lett. 91, 010403 (2003).

22. R. Schnabel, W.P. Bowen, N. Treps, B. Buchler, T.C. Ralph, P.K. Lam and H-A. Bachor, 'Optical Experiments Beyond the Quantum Limit: Squeezing, Entanglement and Teleportation', Optics & Spectroscopy 94, 711–724 (2003).

23. R. Schnabel, W.P. Bowen, N. Treps, B. Buchler, T.C. Ralph, P.K. Lam and H-A. Bachor, 'Stokes-Operator-Squeezed Continuous-Variable Polarization States' Phys. Rev. A 67, 012316 (2003).

24** G. Theocharis, D.J. Frantzeskakis, P.G. Kevrekidis, B.A. Malomed and Yu.S. Kivshar, 'Ring Dark Solitons and Vortex Necklaces in Bose-Einstein Condensates', Phys. Rev. Lett. 90, 120403 (2003).

25.** N. Treps, N. Grosse, W.P. Bowen, C. Fabre, H-A. Bachor and P.K. Lam, 'A Quantum Laser Pointer', Science 301, 940 (2003).

** Impact factor > 5

PUBLISHED CONFERENCE PROCEEDINGS

1. H-A. Bachor, 'Scientific Tools for Future Photonics Applications', in The knowledge revolution in the ACT, p36–40 (ANU NIEIS, 2003).

2. S.A. Brown and B.J. Dalton, 'The Photon Model and Non-Hermitean Modes', in Coherence and Quantum Optics VIII, (N.P. Bigelow et al. (Eds) Kluwer Academic/Plenum) p373–374 (2003).

3. B.J. Dalton, S.M. Barnett and B.M. Garroway, 'Quasimodes and Pseudomodes in Structured Reservoirs', in Coherence and Quantum Optics VIII, (N.P. Bigelow et al. (Eds) Kluwer Academic/Plenum) p495–496 (2003).

4. J.J. Hope, M.K. Olsen and C.M. Savage, 'Quantum Noise in Coupled Atomic and Molecular Bose-Einstein Condensates' in Coherence and Quantum Optics VIII, (N.P. Bigelow et al. (Eds) Kluwer Academic/Plenum) p311–312 (2003).

5. N. Robins, J.J. Hope and C.M. Savage, 'Atom Laser Dynamics' in Coherence and Quantum Optics VIII, (N.P. Bigelow et al. (Eds) Kluwer Academic/Plenum) p583–584 (2003).

6. C.M. Savage, Yu.S. Kivshar, P.J.Y. Louis, E.A. Ostrovskaya, 'Bose-Einstein Condensates in One-Dimensional Optical Lattices: Bandgap Structure and Solitons', CLEO/QELS'03 Technical Digest (Baltimore, Maryland June 1–6, 2003), paper QThJ5.

7. T. Symul, W.P. Bowen, R. Schnabel, N. Treps, B.C. Buchler, T.C. Ralph, A.M. Lance, N.B. Grosse, A. Dolinska, J.W. Wu, J.R. Gao, C. Fabre, H-A. Bachor and P.K. Lam, 'Optical Squeezing in Temporal, Polarization and Spatial Domains', Proceedings of SPIE vol.5111, 67 (2003).

Diane Hutton

Max Colla

ASSETS

The biggest asset for our research is people. We started with an excellent group of people and have given them improved opportunities for research through reduced teaching loads, improved laboratories and offices as well as the opportunity to travel within ACQAO and throughout the world. Some 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 interaction 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) has taken over the financial and organisational work, creating more time for research.

We have been able to attract excellent additional staff. Xia-Ji Liu has joined UQ, G. Duffy at SUT with R. Dall, L. Longchambon, and B. Dabrowska joining the ANU. We are particularly proud that we will soon be able to bring Australians who work overseas back to Australia (B. Hall from the UK to SUT and C. 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 is given on page 38.

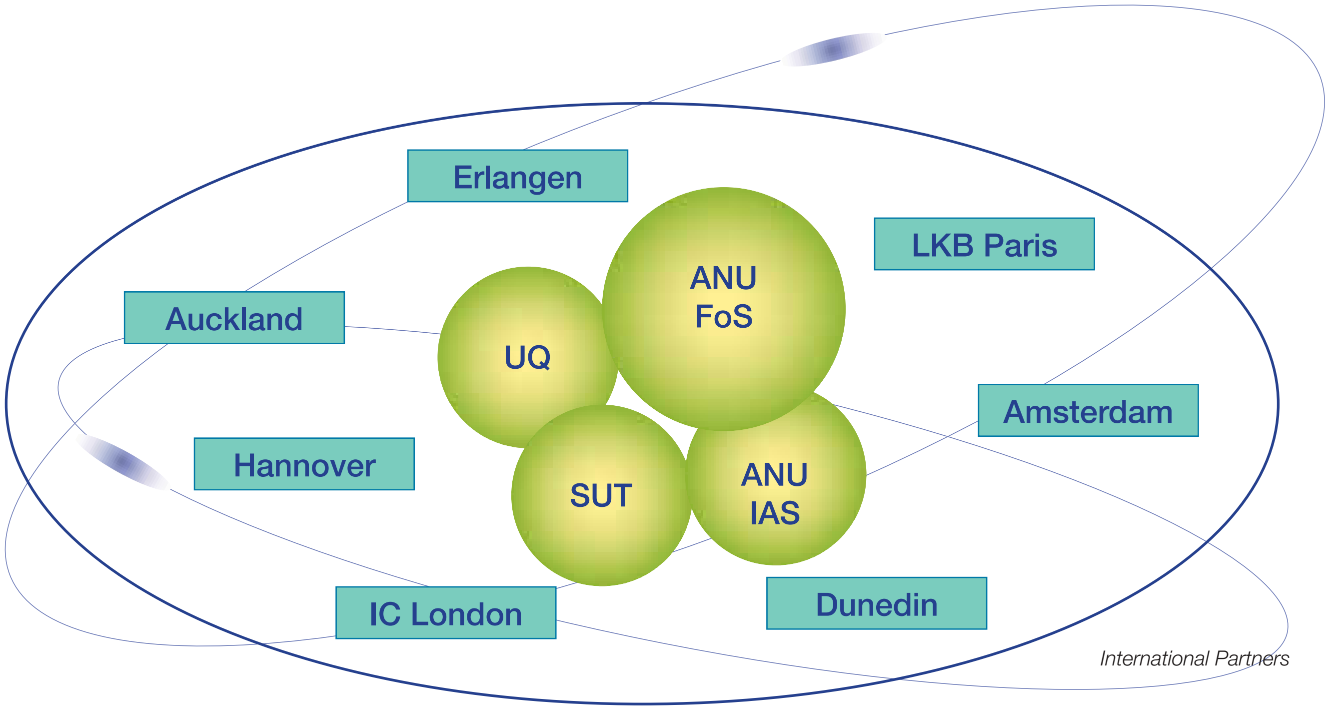
Nick Robins

Ruth Wilson

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 we are building a similar laboratory in the ANU Faculties.

We were able to buy a major piece of equipment, a frequency doubled Ti-Sapphire laser (total cost $498.000) which was installed at the ANU. All of our experiments have gained significantly from a wide

ACQAO team



International Partners

range of new equipment, which makes our work competitive on the global stage.

The Centre was also involved in a successful proposal for the ARC Network Seed Funding led by Deputy-Director Ken Baldwin, for which $30,000 was received (SR0354519). These funds have been used to put forward a full Network proposal (the Network for Optical and Quantum Science and Technology (NOQST) and the Centre for Ultrahigh Bandwidth Devices and Optical Systems (CUDOS), as well as individual research groups around the country. In this way, ACQAO will be able to further enhance its research outcomes and Australia's international profile in these important fields.

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 partners

- Paris on quantum imaging where a cotutelle (joint PhD project) has been established and staff have been exchanged (N. Treps, C. Fabre, H-A. Bachor, L. Longchambon) worked on both sides and have visited (M. Leduc)
- Hannover on BEC on a chip where a joint PhD program (F. Scharnberg) continues
- Amsterdam on He* BECs where researchers travelled in both directions (A. Truscott, Nes and C. Koelemiej)
- London on BEC on a chip where we gain expertise through a post doc (B. Hall joining SUT)
- Dunedin where we have started joint theory projects (R. Ballagh, M. Davis) and a postdoc G. Duffy joining SUT.

In addition we have expanded working relationships with Florence (P. Hannaford, J. Lye joining LENS), a second research institution in Amsterdam (AMOLF — G. Shlyapnikov, K. Kheruntsyan, P. Drummond) and the University of Innsbruck (R. Grimm, A. Sidorov, R. Blatt, H-A. Bachor).

At the moment we are investigating the options for ACQAO participation in European research networks.

We have signed a contract with the Sonderforshungsbereich in Hannover and the CNRS in Orsay to organise annual quantum workshops over three years — one in each country.

In July the leading Laser Spectroscopy conference "International Conference on Laser Spectroscopy" (ICOLS03) was held in Cairns, with the organising team all being members of ACQAO and led by P. Hannaford. This was a spectacular success that brought more then 150 scientists all representing leading research groups, to Australia. It provided a unique opportunity for Australians to have direct discussions with their international counterparts as well as showcasing Australian activities. About 12 scientists extended their visit and travelled to see the activities in all our Nodes.

In addition, in February 2003 the UQ Node hosted a workshop with 8 international visitors in Caloundra which produced excellent discussions. In December 2003, the SUT node helped to organise and ACQAO sponsored the Australian Conference on Optics, Lasers and Spectroscopy with more than 15 international guests. Quantum and atom optics was one of the most active parts of the program.

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.

Poster session at ICOLS03

Commercialization

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

We have received funding of $250,000 from the ACT Government to commence research and commercialization activities in Canberra. We are using these funds for two projects where we are supporting the development of a new, economical technique for locking the frequency of a tunable laser to an atomic transition. J. Close and his collaborator M. Gray have applied for a provisional patent and are actively developing a prototype instrument which will demonstrate the technique to potential manufacturers.

The second project is being carried out by K. Baldwin and A. Truscott who will develop a practical instrument for the measurement of the phase of coherent atoms.

In addition, the UQ group is further developing the software code XMDS (see page 26) which could be licensed commercially in the future.

Outreach

Outreach is an important mission of the Centre and 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 RioTinto Science Olympiads and Questacon.

Staff at ANU contributed to all these programs and reached more than 300 students and 30 teachers.

We organised public lectures by Nobel Laureate W. Phillips (NIST) on “The Coldest Stuff in the Universe” and R.Blatt (Innsbruck) on “Quantum Computers”. These enthusiastic and engaging lectures drew capacity crowds at the ANU and 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 two textbooks (page 28) and the proceedings of the ICOLS conference has helped disseminate our latest scientific results to an international audience.

Ruth Wilson, has started an active PR program with good response in the Press and on TV, detailed on page 34. One particularly successful event was the formal opening of our Centre at ANU in July which attracted many visitors from Overseas and Australia and was well reported in the media.

Hans-A Bachor contributed to one industry forum, the Knowledge Revolution in the ACT, and received widespread interest in the long term commercial aspects of our work. ACQAO also gave presentations to the Victorian Government.

Finally Ping Koy Lam and Warwick Bowen won the Eureka Prize for Inspirational Science and Ken Baldwin was a finalist for the Eureka Prize for the promotion of Science.

KEY PERFORMANCE INDICATORS (KPI)

We believe that the performance of the Centre can be judged by 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 first results. At the same time we are already producing many impressive results, which are described in the Science section (pages 8-26) of this report.

We have well 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 2003 we have exceeded the projected KPIs with 25 publications, including two advanced textbooks. Amongst these are 5 publications (or 20%) with particularly high impact factor in Science and Phys. Rev. Letters. Interaction with the partner institutions is intensifying and we expect to see longer and more intensive exchanges of students and staff internationally and within the Centre.

At the same time, we have maintained a widespread teaching program at all three Universities, with a total of 18 undergraduate courses and presented our ideas, goals to a wide section of the Australian Physics community. For the future we see an even more intensive Outreach program.

AWARDS RECEIVED

Throughout the year members of the Centre were rewarded with a number of distinction which indicate the high profile of our staff.

Prof Hans Bachor	Federation Fellowship
Dr Ken Baldwin	Finalist, Eureka Prize for the Promotion of Science
Mr Warwick Bowen	Australian Postdoctoral Fellow 04
Prof Peter Drummond	Elected to the Australian Academy of Science
Mr Tom Hanna	Monash fellowship to study in Oxford for 3 years
Dr Joseph Hope	AAS Prize in the Campus Review Dialogica Awards
Prof Yuri Kivshar	Finalist, Bulletin Top 100, IBM science category
A/Prof Ping Koy Lam and Mr Warwick Bowen	Eureka Prize for Inspirational Science
Dr Elena Ostrovskaya	Australian Postdoctoral Fellow 03 (level B)
Mr Nick Robins	Australian Postdoctoral Fellow 04
Mr Nick Robins and Mr Warwick Bowen	Australian Academy of Science International Travel Award for Young Scientist
Dr Andrew Truscott	Australian Research Fellow 03 (level C) and AAS Early Career research award

Key Result Area	Performance Measure	Target	Outcome
Research Findings	Quality of publications International Ref. Journals with an impact factor >5	4/25	5/25
	Number of publications/year	20	26
	Number of patents/year	0.3	Provisional 1
	Number of invitations to address and participate in international Conferences/year	4	11
	National and international/Commentaries in professional journals year	3	2
Research Training and Professional Education Number of postgraduates	Recruited/year	5	7
	Number of postgraduates Completions/year	4	4
	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	18
International, National and Regional Links and Network	Number of International visitors/year	10	38
	Number of national and international	1 international	1
	Workshops/year	1 national	1
	Number of visits to overseas Laboratories	18	26
	End-user Links Number and nature of commercialisation Activities	2	1
	Number of government, industry and Business briefings/year	2	2
	Number of Centre associates trained In technology transfer and Commercialisation	2	2
	Number and nature of Public Awareness programs	4	4

PUBLIC RELATIONS/MEDIA

The official launch

The ARC Centre of Excellence for Quantum-Atom Optics (ACQAO) was officially launched July 23, 2003 at The Australian National University Node in Canberra.

The Centre Director, Professor Hans-A Bachor, welcomed over 120 special guests including politicians, Embassy personnel, visiting international scientists including Professors Arimondo (Pisa), Ertmer (Hannover), Leduc (Paris), Eschner (Innsbruck) and Meschede (Paris).

Left to right Professors Aspect, Bachor and Sara

Professor Hans-A Bachor launches the new centre

Members of the ACQAO Advisory Board, Professors William Phillips (USA), Alain Aspect (France), Eugene Polzik (Denmark), Crispin Gardiner (New Zealand), and Dr Bruce Whan (Swinburne Melbourne) attended as well as the Directors from the other three ACQAO Nodes, Dr Ken Baldwin (ANU IAS), Professor Peter Hannaford (Swinburne University of Technology Melbourne) and Professor Peter Drummond (University of Queensland).

Professor Vicky Sara, Chief Executive Officer of the Australian Research Council launched the Centre with an inspiring speech.

Professor William Phillips, National Institute for Science & Technology (NIST) USA Nobel Laureate received loud applause after his enlightening talk on Quantum-Atom Optics and his research.

The guests adjourned to the Centre's new offices and were treated to a tour of the Centre laboratories where the research on the Atom Laser caused the most interest.

Left to right Professor Drummond and Dr Karen Kheruntsyan at UQ

Launch media coverage

Media interest in the Centre launch was strong with wide coverage gained in television, radio and print.

The Launch media release — "New Centre At ANU Set to Unlock Secrets of the Laser" attracted the following exposure:

Television:
Canberra ABC State TV News — Refers ARC
Canberra WIN State TV News — Refers ARC
Swinburne + UQ

Radio:
ABC Radio News 5:00pm — Professor Phillips Refers ARC
ABC Victoria State wide Radio News — Refers ARC
Melbourne 3RN Radio News — Refers ARC
Canberra 106.3FM — Interview Professor Phillips
Canberra 666 — Interview Professor Phillips

Print:

Canberra Times	Page 3 Photo story
Sydney Morning Herald	Page 3 Photo story


Researchers take a quantum leap forward in new lab

Media coverage, 24 July, 2003

Additional centre media coverage in 2003

In August a media release was distributed to support science at the Queensland Node — "Love & Hate Between Atoms on a Wire". Coverage achieved:

Television: Article on ABC Science Online
Radio: Interview with Professor Drummond

Also in August another Media Release — "CDs DVDs… What's Next?" achieved page 3 coverage in the Canberra Times with an interview with Professor Claude Fabre and Professor Hans Bachor regarding the successful research with the new Quantum laser.

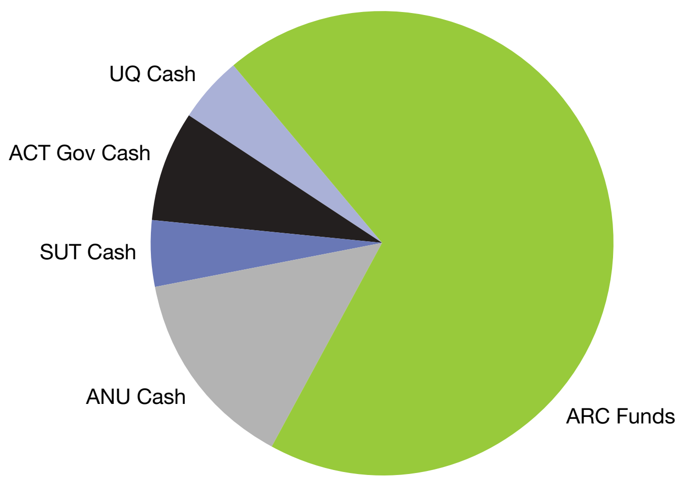

Exciting implications for laser breakthrough

Left to right Professors Claude Fabre and Hans-A Bachor

ACQAO INCOME AND EXPENDITURE 2003

INCOME	$
Australian Research Council	2,241,789.00
The Australian National University	**456,000.00**
Swinburne University of Technology	150,000.00
Australian Capital Territory Government	250,000.00
University of Queensland	150,000.00
TOTAL INCOME	**3,247,789.00**
EXPENDITURE	
ACQAO Contributions to Partners and ANU Facilities	865,896.00
ARC PROJECTS	
Equipment	1,029,009.00
Personnel	435,471.00
Travel	153,302.00
Consumables	88,015.00
TOTAL EXPENDITURE	**2,571,693.00**
ACCUMULATED FUNDS	**676,096.00**

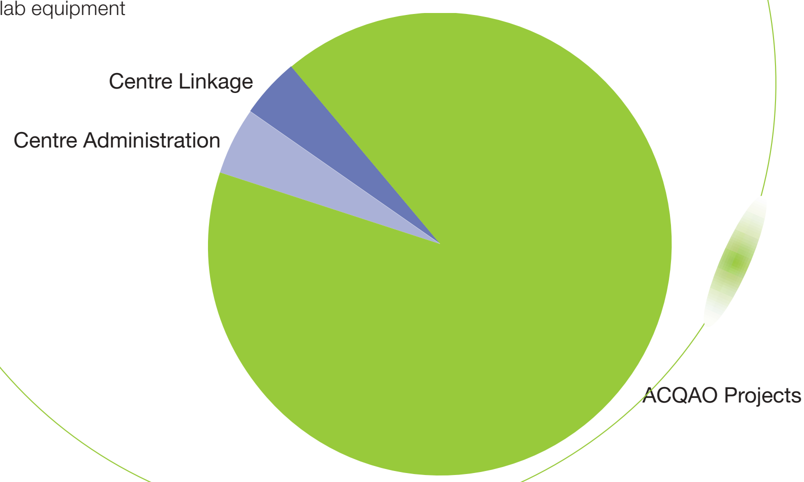
Notes: Accumulated funds to be rolled into 2004
(Funding commenced June 2003)
2003 funds from Queensland Government to be paid in 2004



ACQAO EXPENDITURE 2003

PROJECTS	$	PROJECTED BUDGET 2004 $
Quantum Imaging	59,244.00	386,293.00
Entangling Atoms & Light	6,330.00	135,589.00
Rb Atom Laser	172,129.00	211,031.00
Quantum Statistics of He*BEC	220,491.00	303,868.00
ANU FAC Theory	115,522.00	314,922.00
ANU IAS Theory	69,476.00	172,907.00
Molecular BEC	189,851.00	241,140.00
Coherence of BEC on a Chip	20,074.00	248,426.00
SUT General	34,968.00	265,031.00
UQ Theory	104,375.00	739,825.00
IAS General	86,482.00	120,517.00
Commercial Development	103,641.00	146,359.00
Large Equipment	371,625.00	18,375.00
Centre Administration	80,080.00	135,186.00
Advisory Board	29,376.00	32,484.00
Organising Science Workshops	20,000.00	51,200.00
International collaboration	17,739.00	58,220.00
Travel within Centre	4,394.00	42,445.00
TOTAL EXPENDITURE 2003	1,705,797.00	3,622,878.00

Notes:
SUT General: Personnel salaries and consumables
IAS General: Technical and personnel salaries
UQ Theory: Includes personnel, travel, equipment, consumables and administration
Large Equipment: Ti Sapphire Laser and lab equipment



* Copy re large equipment to come

ACQAO 2003 PERSONNEL

Below is a list of all Staff and Students including Honours/Undergraduates with project work in ACQAO during 2003.

Prof Hans-A Bachor
Dr Ken Baldwin
Ms Ruth E Wilson
Mr Max Colla
Prof Peter Hannaford
Mrs Sharon Jesson
Prof Peter Drummond
Ms Diane Hutton
Prof Yuri Kivshar
Mrs Wendy Quinn
Dr Elena Ostrovskaya
Prof. Fel Andrei Sidorov
Prof. Fel Tien D Kieu
Prof. Fel Russell McLean
A/Prof Bryan Dalton
Dr Wayne Rowlands
A/Prof Craig Savage
Dr Joseph Hope
Dr John Close
Prof Mike Kruger
A/Prof Ping Koy Lam
Dr Andrew Truscott
Dr Matthew Davis
Dr Karen Kheruntsyan
Dr Joel Corney
Dr Margaret Reid
Dr Paul Cochrane
Dr David Lau
Mr Heath Kitson
Mr Greg Collecut
Mr Robert Dall
Ms Laura Noack
Mr Christian Weedbrok
Ms Johanna Nes
Mr Nick Robbins
Mr Warwick Bowen
Mr Magnus Hsu
Dr Laurent Longchambon
Mr Sebastian Wuester
Ms Beata Dabrowska
Mr Tristram Alexander
Ms Pearl Louis
Mr Falk Scharnberg
Mr Shannon Whitlock
Mr Simon Haine
Ms Adele Morrison
Mr Tom Hanna
Mr Peter Kuffner
Mr James Swanson
Dr Jessica Lye
Mr Cameron Fletcher
Mr Thomas Argue
Mr Kurt Erlich
Mr Andrew Ferris
Mr Tim Vaughan
Mr Piotr Deuar
Mr Mark Dowling
Mr Brian Kasch
Mr Magnus Ógren
Ms Camille Breme
Mr Julien Dugue

Contact Us:

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