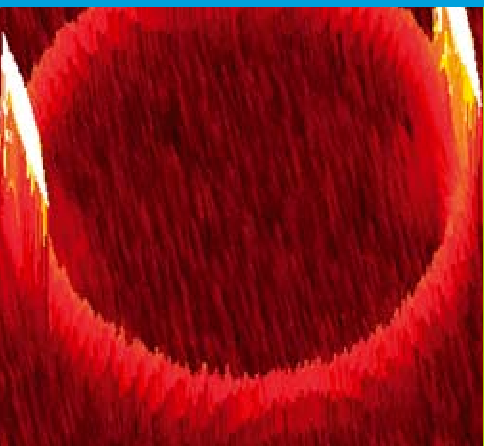

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report for the year 2007

THE AUSTRALIAN NATIONAL UNIVERSITY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

SWINBURNE UNIVERSITY OF TECHNOLOGY

Australian Government

Australian Research Council

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FOREWORD

Quantum-Atom Optics is expanding internationally as a field of research and our Centre in Australia is right in the middle of the action. We have now successfully concluded the first phase of our programme and achieved all the goals we set ourselves for the first five years. The investment in our Centre is paying off and we are now looking forward to investigating new fundamental science ideas as well as perfecting our instruments to make quantum technology accessible to future applications.

The Australian Research Council Centre of Excellence for Quantum-Atom Optics (ACQAO) is a key part of Australia's contribution to the rapid development of quantum science and technology. We concentrate on fundamental science questions and create the scientific tools for the engineers of the future, who will utilise the effects based on the quantum properties of atoms and photons. Together with our partners in Europe, the USA and New Zealand we create the foundations of a diverse range of quantum technologies in areas such as information processing, communication, sensing and imaging.

Our strength is that we understand and can demonstrate the special quantum properties of large objects, involving thousands or even millions of atoms, and observe the transition from the microscopic world of a few particles to the macroscopic classical world.

This is now very relevant since industry is using more and more devices that are based on nanoscale objects and the quantum effects appear more frequently, either as limitations to classical engineering or as opportunities to apply completely new concepts. The interface between microscopic quantum and macroscopic classical engineering will be the source for new practical innovations.

Entanglement, the exact link that can be created between two particles or even systems, is at the core of these quantum phenomena. We have considerable success demonstrating entanglement between photons, we are developing ideas for generating and testing entanglement between many particles and we are aiming at generating beams of atoms that are entangled.

ACQAO combines in a unique way expertise in the quantum properties of light and atoms, the theory of quantum statistics and nonlinear interactions with the operation of non-classical light sources and Bose-Einstein condensates, (BECs) which are quantum systems of many atoms. In ACQAO, scientists from across Australia collaborate, with teams at the Australian National University (ANU) in Canberra, at the University of Queensland (UQ) in Brisbane and at the Swinburne University of Technology (SUT) in Melbourne.

Since the inception of ACQAO we have developed many joint projects and the sharing of knowledge, expertise and equipment within the Centre and with our international partners this has allowed us to achieve our goals faster and more efficiently. We have shown how productive such a virtual Centre can be and we have ensured that Australia's contribution to the development of quantum technology is now widely recognised.

Highlights of our work in 2007 include the demonstration of a molecular BEC with Li atoms at SUT, the discovery of universal thermodynamic properties of strongly interacting fermions, the operation of the first pumped atom laser with high beam quality and the demonstration of spatial optical entanglement.

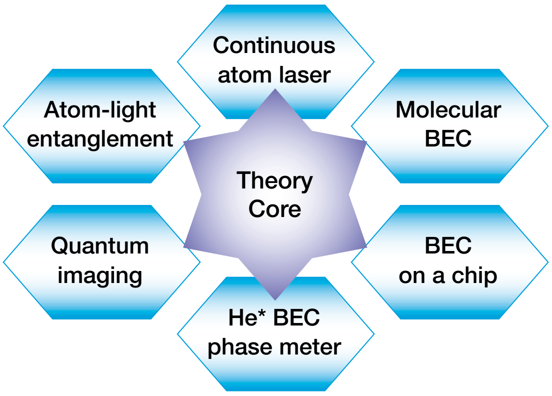
ACQAO is part of the vision of the ARC to promote excellence in the most successful research fields. This is made possible by combining funding from the ARC, the three Universities and the Defence Science & Technology Organisation (DSTO). With this support we can tackle a well-defined set of ambitious and visionary projects, train outstanding postgraduate students and raise the awareness of the wider community of the opportunities created by strategic fundamental research. Our model of a national centre and the vision of combining optical and atomic quantum physics have been adopted in the formation of Centres of Excellence in Germany, France, USA, Singapore and New Zealand.

The first international conference on quantum-atom optics was hosted by ACQAO in Wollongong, Australia, with 70 international delegates and demonstrated the central role our Centre plays in this expanding research area.

This report presents our new achievements, in the form of many science summaries that show the technical details and the ideas of our theory teams and experimental projects. I hope this stimulates your interest in our quest to lay the foundations for future quantum technologies.

Professor Hans-A. Bachor
Research Director

QUANTUM-ATOM OPTICS — BACKGROUND AND RESEARCH HIGHLIGHTS



Our research goals

Most applications of optics are based on 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 includes in addition, the effects based on the quantisation, or particle nature, of light.

The field of Photonics, which uses lasers as the source of coherent light, was until now essentially based on classical optics and will benefit soon from the advances in quantum optics. In the last few years it has become easier to isolate the quantum effects of light and they appear more frequently as a limit in the quality or sensitivity of optical instruments. In addition, quantum optics offers new possibilities for the communication of information. Australia has established a strong international research profile in this field, both through pioneering theory work as well as state of the art experiments.

We normally consider atoms as particles interacting via collisions in a gas or being close to each other in a liquid or solid. Now atoms can be manipulated, cooled and stopped and they can be detected individually, one at a time with increasing efficiency. However, atoms also have wavelike properties, they can be described by quantum mechanical wave functions and the interference between their probability amplitudes. We are now in the position to build atom lasers that produce coherent matter waves and we will soon be able to study the quantum statistical properties of atoms in a way similar to optics. This opens the way for new examples of quantum technology, such as improved sensors based on atom interferometry. In ACQAO we are developing and enhancing the links between quantum optics and atom optics.

Entanglement

Entanglement is one of the key concepts of quantum physics. It describes the properties of two systems, which originate from one source, and are in the ideal case indistinguishable. For example, these could be two laser beams created in one source, propagating in different directions and which contain identical information, modulation and noise. Or they could be two, or more, beams of particles that have identical properties. Some of the pioneering theory work on entanglement was carried out in Australia and the extension to systems of many particles [p. 29 Reid] is one of the goals in ACQAO.

The ANU researchers have already built optical sources that produce strong noise suppression, and entanglement. Within ACQAO, we will use this special light to demonstrate spatial effects, such as the precision measurement of the position and direction of laser beams and the communication of spatial information. We have now succeeded in demonstrating such spatial entanglement [p. 28 Wagner] and show that it satisfies the criteria discussed by Einstein, Podolsky and Rosen in the 1930s. While entanglement between individual atoms has been studied in detail we are now asking the question how we can describe and generate entanglement between many particles. We are developing new tools to make these effects visible.

Creating and containing Bose Einstein Condensates

Groups of atoms can be manipulated, cooled, stopped and trapped until they reach such a low temperature that the atomic deBroglie wave and quantum effects will dominate. Theory has shown some years ago that the centre-of-mass wave function of atoms can be made to interfere.

Bosonic atoms such as Rubidiumb 87, Caesium 133, and metastable Helium 4 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 cold atoms. We have developed techniques to study the details of this transition both in experiments and through simulations [p. 25 Davis].

Australia now has six BECs, four in Rubidium and one each in metastable Helium and Lithium. All are optimised for different studies and applications. Five of these are part of ACQAO and are used to further refine the technology, to make the apparatus simpler and more reliable for applications. For example, the two Rb 87 BECs at SUT are based on an unique technology which uses permanent magnets with micron-sized structures to guide, trap and condense the atoms. This allows us to reduce the size and complexity of the apparatus and we can contain the BEC for longer with fewer losses than other groups. The SUT technology will allow us to build small, reliable BEC instruments, which can be developed into robust and very sensitive sensors, based on atom interferometry. It is now possible to create two-component BECs which are the basis of future applications in controlled chemistry [p. 22 Anderson]. The metastable He BEC at the ANU is highly controlled and allows us to investigate the properties of the BEC using detectors sensitive to single atoms. This system will be used to investigate the statistical nature of the BEC and to probe deeper into the quantum properties of this atomic system.

Atom Laser and transferring entanglement

It is one more step from the BEC to the atom laser, a device that produces a coherent beam of atoms. In 2007 we showed the operation of an atom laser with metastable Helium 4 and investigated the interference of the different matter waves reaching the detector. [p. 13 Dall1]. With the Rubidium apparatus we are developing new techniques that improve the quality of the laser beam, the intensity and beam shape. In this way we will turn the atom laser into a practical device for precision experiments in analogy to the development of optical lasers in the 1960s and 70s. We have now built an optimised BEC apparatus that produces larger atom numbers, has better controlled properties and is the first atom laser that is actually pumped from an external reservoir of atoms [p. 10 Robins].

This Centre combines, in a unique way, quantum optics and atom optics, theory and experiments. We have developed a clear vision and detailed plans for a novel apparatus that converts quantum correlations from optical laser beams to quantum correlations in the atom laser beams. This ambitious project will bring together many of our experimental skills such as generating tunable non-classical light and single atom detection, as well as detailed model calculations [p. 12 Johnsson], [p. 11 Bradley].

In parallel we are investigating ways of transferring quantum correlations from light to atoms and vice versa as an initial step in designing atomic storage for optical quantum information. Through international collaborations we investigated different options for the storage of nonclassical light. We were able to show that information can be delayed in time using electromagnetic induced transparency (EIT) [p. 32 Vanner] using Rubidium, and are now applying this technique to squeezed light. An alternative proposal using the concept of photon echoes for storing and retrieving quantum information is even more promising [p. 33 Hetet]. Related experiments on quantum information, communication and cryptography are making rapid progress and are carried out independently of ACQAO at the ANU, in other laboratories in Australia and around the world.

From Bosons to Fermions

Recent years have seen a very rapid development of the theory concepts and the experiments with Fermions. Atoms can combine into molecules, they can dissociate forming pairs of Fermions and in well controlled situations this can lead to quantum correlations of individual atoms as well as among many particles. We have now shown for the first time in Australia the formation of a molecular BEC of fermionic Lithium6 atoms [p. 19 Fuchs1]. This will allow a detailed investigation of Fermion interactions. In addition we have created a new understanding of universal features in the quantum statistics of Fermions [p. 18 Liu] which is being tested by experiments overseas.

Leading the way to the future

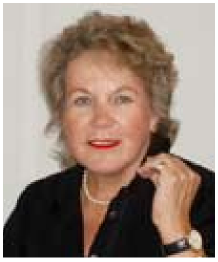
All these experimental goals are underpinned and frequently initiated by a very strong theory core in ACQAO, which combines the expertise of world-renowned researchers. The different techniques and expertise from quantum optics, field theory and nonlinear optics are combined within one powerful group of scientists who guide and support the experimental work. In some cases the theory is well ahead of the experiments. Examples are new ideas for applications of nonlinear matter wave interactions [p. 40 Lee], [p. 36 Dabrowska Wuester], [p. 24 Perrin]. In other cases the new techniques developed in ACQAO can explain experiments in other laboratories in an elegant and complete way, both for optical sources [p. 31 Corney] and for atomic systems [p. 21 Savage].

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 new ideas, experimental demonstrations and simulations. This work over the next five years paves the way for applied work in quantum technology in 10–15 years. The Centre does this by combining the separate scientific concepts, by linking the leading scientists in Australia and by developing an exchange with our partners in Europe, who are in some of the most productive groups in this field. In this way ACQAO is an important part of a global research effort and ensures that future optical quantum technology will be developed and remains accessible to Australia.

THE NODES — STRUCTURE OF THE CENTRE

The Centre combines many of the leading scientists in quantum and atom optics in Australia, and is underpinned by a theory core operating across all nodes that interacts closely with the six experimental programmes located at ANU and Swinburne. We have thriving teams in three locations: Canberra, Melbourne and Brisbane, which are linked through joint scientific projects, the sharing of expertise and equipment and the exchange of people. The scientific goals have been chosen to be ambitious and after five years we have now achieved all our initial goals. We are expanding the frontiers of knowledge in quantum and atom optics by employing the expertise of all members of the Centre.

The Centre is coordinated from the Australian National University (ANU) by the Research Director, Hans-A. Bachor and the Chief Operations Officer (COO), Ruth Wilson. The science is carried out by a theory core group and six experimental projects. At the end of 2007 we had a total staff of 51 plus 44 students.

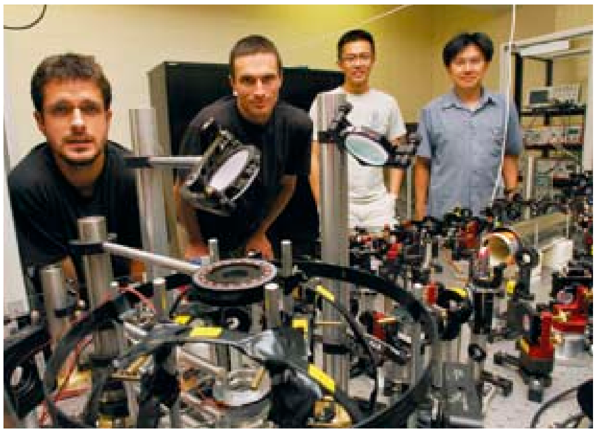


Ruth Wilson

ANU FAC, Canberra

Hans-A. Bachor

At the ANU we have the research node which carries out experimental work with Rb BECs, demonstrating for the first time a unique pumping mechanism for an atom laser (John Close, Nick Robins, Cristina Figl) . This node also undertakes experiments on quantum imaging, spatial entanglement (Hans-A. Bachor, Ping Koy Lam) and tunable entangled light which also shows the transfer of quantum correlation from light to atoms and the storage of quantum correlations (Ben Buchler, Ping Koy Lam). This is complemented by innovative theory (Joe Hope, Craig Savage, Mattias Johnsson) that concentrates on the properties of coherent atom sources, quantum feedback, atom light entanglement and correlated atom lasers, and work with the other theoretical groups at the UQ and SUT to stimulate experimental advances in the all nodes.



Atom Light Entanglement group L to R: Gabriel Hetet, Ben Buchler, Magnus Hsu, Ping Koy Lam

ANU IAS, Canberra

Ken Baldwin

On the other side of the ANU campus, in the Institute of Advanced Studies (IAS) and located within the Research School of Physical Sciences and Engineering, we have a node that combines theory and experiments. The laboratory now has a precisely controlled He* BEC which allows investigations of quantum interference in the atom laser output, and precision spectroscopy which makes quantum statistical effects accessible through single atom detection (Andrew Truscott, Robert Dall and Ken Baldwin, who is Node Director and Centre Deputy Director). The theoretical group has world leading experience in nonlinear optics, optical lattices and soliton physics (Yuri Kivshar, Tristram Alexander, Chaohong Lee, Elena Ostrovskaya) and their focus is on the properties of nonlinear matter waves and their effects in optical lattices and other periodic structures.

AIS team L to R: Deborah Bordeau, Katy Hicks, Chaohong Lee, Ken Baldwin, Sean Hodgman, Elena Ostrovskaya, Yuri Kivshar, Lesa Byron, Michal Matuszewski, Tristram Alexander, Dario Poletti

UNIVERSITY OF QUEENSLAND, Brisbane

Joel Corney

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

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

SWINBURNE UNIVERSITY OF TECHNOLOGY, Melbourne

Peter Hannaford

At Swinburne University of Technology (SUT), the Centre has two experimental projects and laboratories located in the Faculty of Engineering and Industrial Sciences with Peter Hannaford as Node Director. SUT has pioneered the use of micro-fabricated permanent magnet structures for unique Rb BECs on a chip (Brenton Hall, Peter Hannaford, Russell McLean, Andrei Sidorov). In parallel, a molecular BEC of Lithium 6 atoms has been successfully set up which allows the study of scattering of molecules and the quantum correlations of Fermions (Chris Vale, Wayne Rowlands, Peter Hannaford). A small theory group complements this work (Bryan Dalton, Chris Ticknor).

Back row L to R: Alexander Akulshin, Will Brown, Bryan Dalton, Eva Kuhnle, Michael Vanner, Gopisankararao Veeravalli, Holger Wolff, Brenton Hall, Peter Hannaford, Andrei Sidorov, Mark Kivinen, Russell Anderson, Mandip Singh, Tatiana Tchernova, Russell McLean, Chris Vale
Front kneeling L to R: Chris Ticknor, Saeed Ghanbari, Paul Dyke

Linkages across the Centre

The nodes are linked through several joint scientific projects including BEC on chip (ANU IAS, SUT), single atom detection funded by LIEF (ANU FAC, SUT, UQ), quantum correlations with Fermions (ANU FAC, UQ), Fermion statistics (UQ, SUT) and BECs in lattices (UQ, ANU IAS).

In addition to the personnel mentioned here, the Centre includes a number of postdoctoral fellows, graduate students and visiting fellows, and all are listed on page 54. The administration includes research assistant Max Colla and Caroline Christenson (ANU FAC) with other administrators Stephanie Golding (UQ), Tatiana Tchernova (SUT) and Wendy Quinn/Kathy Hicks (ANU IAS).

GOVERNANCE

In March 2007 The Australian Research Council confirmed funding support for a further three year extension for our Centre from 2008 through 2010.

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

The fundamental decisions for the Centre are determined by all Chief Investigators that are achieved during bi-annual CI meetings (Caloundra May 2007, Wollongong December 2007). The ongoing administration is supervised by the Executive Committee, which meets four times a year. Node Directors are responsible for the continuous operation of the four nodes. Regular science meetings were held fortnightly within the nodes.

The COO is responsible for the daily administrative work with support from the administrative officers at SUT, UQ and the IAS. The financial status and science progress are reported to the COO and Research Director on a quarterly basis via the Node Directors.

Centre Management Meetings			
CI meeting	All CIs & COO	Bi-annual	May, Caloundra December, Wollongong
Executive Board	Res Dir. & COO, Node Directors	Quarterly	3 meetings in Canberra 1 Wollongong
Advisory Board	International & national members	Annually	December, Wollongong
International Workshop	Centre & partners, other AUS groups	Bi-annual	May, Caloundra December, Wollongong
Individual Project & group	Staff & students, visitors	Fortnightly	
IP committee	Node directors, Universities	Annually	

Advisory Board

The members of the Advisory Board have provided continued expertise both in areas of international science and with advice on potential end-users of our research. We are fortunate that the high profile international members attend our workshops and provide us with detailed feedback on the standing of our work in the international arena.

The 2007 members of the Board are:

Prof David Pegg, Griffith University, Brisbane Australia, tendered his resignation late 2007 because of his retirement.

Prof Alain Aspect, Institut d'Optique, Palaiseau, France

Prof Keith Burnett, Oxford University, United Kingdom

Prof William Phillips, Nobel laureate, NIST Maryland, USA

Prof Eugene Polzik, Niels Bohr Institute, Copenhagen, Denmark

Senator Gary Humphries

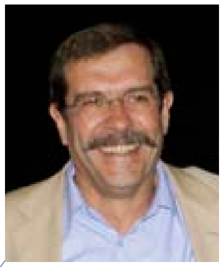
Bob McMullan MP

Steven Duvall, Corporate Consultant

Dr Bruce Whan, SUT

David Wilson, DSTO

Advisory Board members

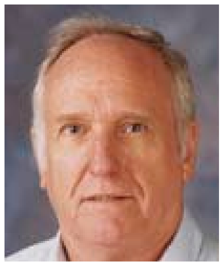


Professor Alain Aspect

Professor Keith Burnett

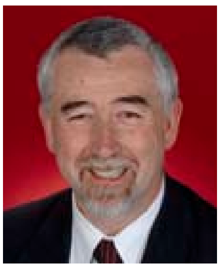
Professor William Phillips

Professor Eugene Polzik

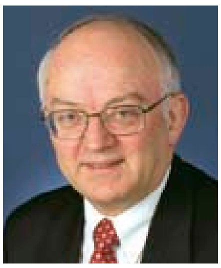


Professor David Pegg

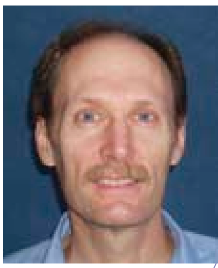
National Board members



Senator Gary Humphries



Bob McMullan MP



Steven Duvall

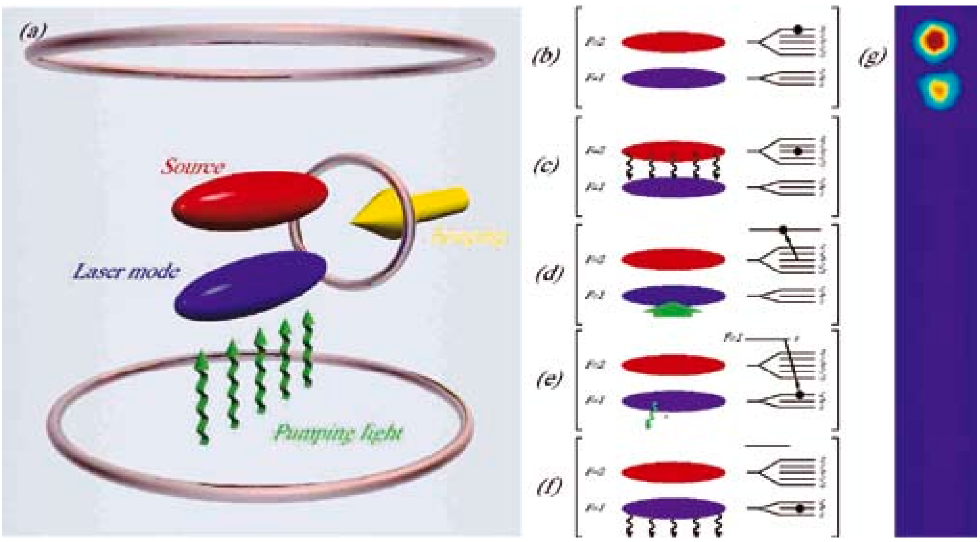
Dr Bruce Whan

David Wilson

A pumped atom laser

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

The invention of the optical laser, a bright, pumped source of coherent photons, has revolutionized optics and precision measurement, led to global high bandwidth communication and enabled non-linear optics, quantum optics, and experimental investigations of quantum information, quantum computing and quantum cryptography. The atom laser, a bright, coherent matter wave, holds similar promise for precision measurement and will open new avenues for fundamental tests of quantum mechanics [1]. Atom laser beams are derived from the exotic state of matter known as a Bose-Einstein condensate (BEC), first produced in dilute alkali gases in 1995 [2, 3]. These incredibly delicate states exist at almost zero temperature and exhibit many of the properties of optical lasers. Despite significant experimental efforts, no method has been demonstrated to continuously and irreversibly replenish the fragile Bose-Einstein condensate that forms the laser mode. This process, known as pumping, is considered an essential feature of any true laser [4]. Here we demonstrate a system for pumping a continuous atom laser, in direct analogy to the optical laser. It has taken a decade since the production of the first pulsed atom laser[5] to surmount a number of serious theoretical and technical hurdles. In our work, we show how we have solved these challenges, demonstrating that while continuously output-coupling an atom laser beam we can simultaneously and irreversibly pump new atoms from a physically separate cloud into the trapped Bose-Einstein condensate that forms the lasing mode.



Schematic of the experiment (a) and pumping steps (b-f). A radio frequency field spin-flips the atoms to the $|2,0\rangle$ state (b), and they fall under gravity (c). The light field couples the atoms to the F′=1 excited state from which they are stimulated to emit into the $|1,-1\rangle$ BEC. The atomic momentum is canceled from the absorption and emission of the photons (d) and (e). A second radio frequency field finally output-couples the atoms into the $|1,0\rangle$ atom laser (f). (g) Absorption image of the experimental system, showing source, laser mode and output beam.

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Quantum state transfer in a Raman atom laser system

A. S. Bradley[1], M. K. Olsen[1], S. A. Haine[1] and J. J. Hope[2]
[1] *ACQAO, School of Physical Sciences, University of Queensland, Australia*
[2] *ACQAO, Department of Physics, Australian National University, Australia*

The ability to measure and manipulate the quantum state of an optical laser has allowed for the testing of some fundamental aspects of quantum mechanics, such as Bell's inequality, the Einstein-Podolsky-Rosen paradox, and quantum teleportation, for the first time. This theoretical research focusses on developing techniques which will allow similar breakthroughs in the field of *atom* optics. We have previously shown that atom laser beams which display exotic quantum properties, such as squeezing and entanglement, can be generated with existing experimental techniques [1]. However, measurement of the quantum state of a matterwave is an unresolved challenge. This is because techniques such as homodyne detection are much more difficult in matterwave systems than optical systems, due to the difficulty of obtaining the matterwave analogue of a mode-matched local oscillator, and efficient atom detection. We have developed a scheme for measuring the quadrature statistics of an atom laser beam using existing optical homodyning and Raman atom laser techniques. A reversal of the normal Raman atom laser outcoupling scheme is used to map the quantum statistics of an incoupled atomic beam to an optical probe beam, where the standard techniques of optical homodyne detection can be implemented. A multimode model of the spatial propagation dynamics shows that the Raman incoupler gives a clear signal of de Broglie wave quadrature squeezing for both pulsed and continuous inputs. We have shown that experimental realisations of the scheme may be tested with existing methods via measurements of Glauber's intensity correlation function [2].

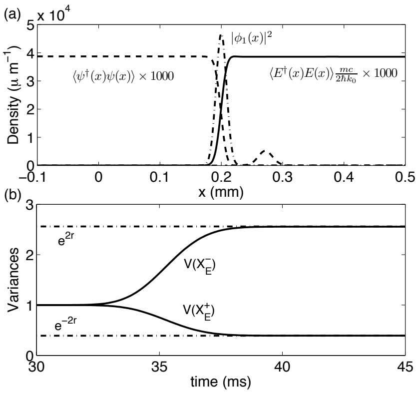

Figure 1: (a) A squeezed atomic beam is coupled into the condensate. (b) Variance of the quadratures of the emitted optical field.

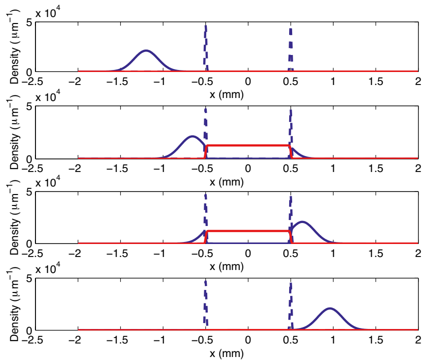

Figure 2: A pulse of atoms enters a condensate, which causes the stimulated emission of an optical beam containing the quantum statistics of the original atomic pulse. The atomic pulse is retrieved when the optical field enters a second condensate.

We have developed a scheme for the disembodied transport of a macroscopic matterwave over large distances at the speed of light. By combining the Raman incoupler scheme with the Raman outcoupler scheme [1], we have shown that a pulse of approximately 5000 atoms can be transported over a large distance by encoding their quantum statistics onto an optical field by using the atomic stimulated transition of the atoms into a condensate, and then retrieving this pulse at a second condensate in a separate location [3]. In practice, the efficiency of this disembodied transport may be much higher than is possible in alternate schemes such as quantum teleportation, as the fidelity of quantum teleportation is limited by the quality of the available entanglement resource.

References

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Generating squeezing in an atom laser through self interaction

M. T. Johnsson and S. A. Haine
ACQAO, Department of Physics, Australian National University, Australia

The creation of the optical laser and the development of quantum optics has allowed tests of many fundamental properties of quantum mechanics. The ability to create quadrature squeezing is an important prerequisite for many of these tests as it allows the creation of continuous variable entanglement between the amplitude and phase of two spatially separated optical beams. With the advent of the atom laser, there has been much interest in creating a quadrature-squeezed atomic rather than optical beam as it allows us to revisit many of these tests using massive particles rather than photons. A squeezed atom laser also offers the possibility of beating the standard quantum shot-noise limit in atom interferometry.

The standard scheme to create a squeezed atom laser is to use a squeezed optical field to couple atoms out of a Bose-Einstein Condensate (BEC) and into the atom laser beam, attempting to transfer the quantum state of the light onto the atoms. Such a scheme is challenging, as it requires squeezed light at the relevant transition frequencies of the atomic species making up the BEC.

We have devised a scheme that allows the creation of a quadrature squeezed atom laser without requiring squeezed light as input, removing a significant source of complexity and cost. Our method utilizes the nonlinear interaction between atoms to generate squeezing via the Kerr effect.

To accomplish this we begin with a dense, tightly confined BEC in a strong magnetic trap. A beam of atoms is outcoupled from the BEC via either a Raman or RF transition, forming the laser beam. As the outcoupling process functions as a weak beam splitter, the atoms in the beam are initially in a coherent state and are not squeezed.

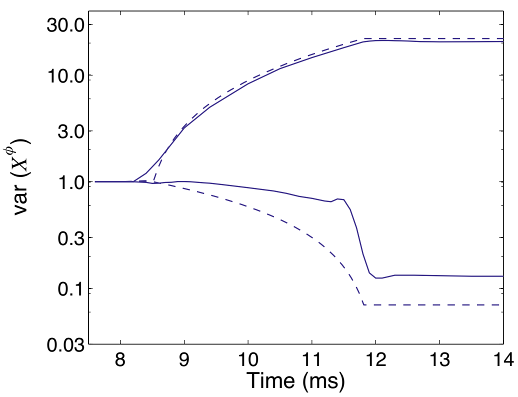

Figure 1: Quadrature squeezing (lower lines) and anti-squeezing (upper lines) of a Rb atom laser for a single-mode analytic (dashed lines) and a multimode stochastic (solid lines) model.

As the atoms fall under gravity, in the short time limit their nonlinear interactions result in a Kerr effect that transforms the coherent state into a quadrature squeezed state. If these interactions were to remain in effect indefinitely, the squeezing would begin to degrade. This is remedied, however, by the fact that as the atom beam falls under gravity it accelerates, reducing the density of the beam. As the Kerr effect is density dependent, the squeezing process ends after a certain fall distance, meaning the beam remains squeezed over its entire length.

We modelled a ^{87}Rb atom laser under our scheme using realistic parameters and quantified the degree of quadrature squeezing we obtained. The results are shown in Fig. 1, and indicate that significant quantities of squeezing can be obtained in realistic experiments, even if multimode effects are taken into account.

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Observation of transverse interference fringes on an atom laser beam

R. G. Dall[1], L. J. Byron[1], A. G. Truscott[1], G. R. Dennis[2], M. T. Johnsson[2] and J. J. Hope[2]
[1] *ACQAO, Research School of Physical Sciences and Engineering, Australian National University, Australia*
[2] *ACQAO, Department of Physics, Australian National University, Australia*

Like its optical counterpart, the atom laser has the potential to revolutionise future atom interferometric sensors, in which a high flux of collimated atoms is required. The ultimate performance of such sensors will rely on the signal-to-noise ratio with which atoms in the atom laser beam can be detected. In the case of a metastable helium atom laser, its constituent atoms are not in their true electronic ground state, but rather in an excited state containing 20 eV of energy. This large internal energy is enough to liberate electrons from a surface when struck by the atom, making detection of single metastable atoms possible. It is this single atom detection property that makes a metastable atom laser not only a promising candidate for future atom laser applications but also as a high resolution probe of fundamental atom laser properties.

Unlike an optical laser, the particles in an atom laser interact with each other by scattering. At ultracold temperatures this scattering can be characterised by a single parameter, the s-wave scattering length. In most cases these interactions are small since the average density in a typical continuous wave (cw) atom laser beam is low. However, as the atoms in the beam are coupled out, they probe the high density of the BEC via the same interactions, and experience a large repulsive force (so-called 'mean field' repulsion).

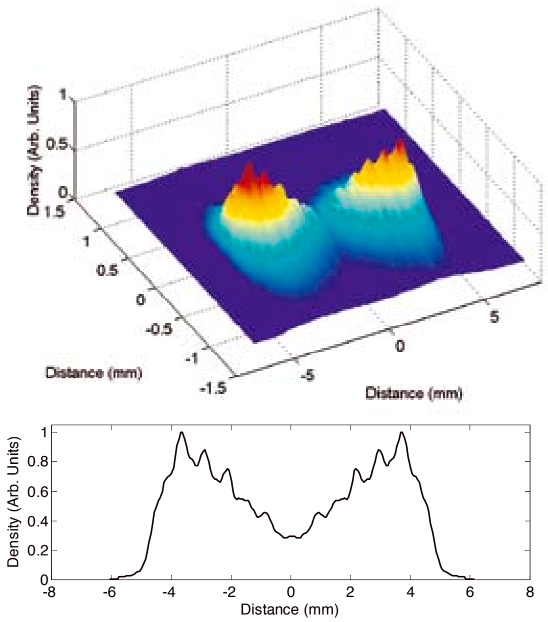

Figure 1: Experimental MCP image (upper plot) and cross-section (lower plot) showing interference fringes. Upper trace is the raw 2-D image, while the lower trace is an averaged profile.

These interactions heavily distort the atom laser beam, resulting in a profile that exhibits a double peaked structure due to classical effects, referred to as 'caustics' [1]. Besides these large-scale classical effects, it has been predicted that interference fringes should be present on an atom laser beam. Atoms starting from rest at different transverse locations within the outcoupling surface can end up at a later time with different velocities at the same transverse position, leading to quantum mechanical interference [2, 3].

Recently, we have made use of the novel detection capabilities offered by metastable atoms to image the two-dimensional transverse profile of our radio-frequency (RF) output-coupled atom laser beam. Moreover, we have observed for the first time interference fringes on an atom laser beam, demonstrating the transverse coherence of an atom laser. An image from our experiment is shown in figure 1.

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Characterising the linewidth of an atom laser

M. T. Johnsson, S. A. Haine, J. J. Hope, N. P. Robins, C. Figl, M. Jeppesen, J. Dugué and J. Close
ACQAO, Department of Physics, Australian National University, Australia

One of the most important properties of a laser is its linewidth, with a narrow linewidth essential for applications such as interferometry and spectroscopy. This is the case for both optical and atom lasers, making it vital to understand what can affect the linewidth and what the lower limit to linewidth is in a variety of regimes.

We have characterised the linewidth of an atom laser for a variety of cases, using both a semiclassical model [1] and a quantum field theory model [2]. Our semiclassical calculations demonstrate that for short times the linewidth of an atom laser can approach the Fourier limit. For longer times, however, the source condensate becomes depleted, leading to an energy drift, or "chirp", in the laser, broadening the linewidth. We have demonstrated a scheme using a time-dependent detuning to compensate for this effect, enabling us to recover the Fourier limit, leading the linewith to be bounded by the drain time of the condensate. Figure 1 shows effect of the compensation scheme on the linewidth of a typical atom laser. This semiclassical analysis suggests that there is no lower limit on the linewidth, provided outcoupling is arbitrarily weak.

Our fully quantum analysis, however, demonstrates that this is not necessarily the case. Our calculations show that the fundamental number uncertainty in the condensate gives rise to an energy uncertainty through the atomic nonlinear interactions. This in turn leads to a hard lower limit on the energy spread of the atom laser beam, that is, a lower bound on the linewidth. This behaviour is shown in Figure 2: at short times the quantum model agrees with the semiclassical model, but at longer times the linewidth of the quantum model hits a lower bound, while the semiclassical model allows the linewith to decrease without limit. The red horizontal line is the limit predicted by our analytic single mode quantum model; the slight reduction below this in our stochastic simulations is due to multimode effects. As futher confirmation of our model, we also simulated an atom laser sourced from a number squeezed condensate, and obtained a reduction in the lowest linewidth that could be achieved.

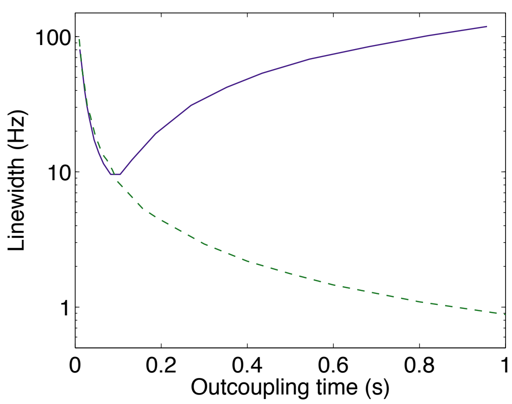

Figure 1: Linewidth of an atom laser with (dashed) and without (solid) chirp compensation.

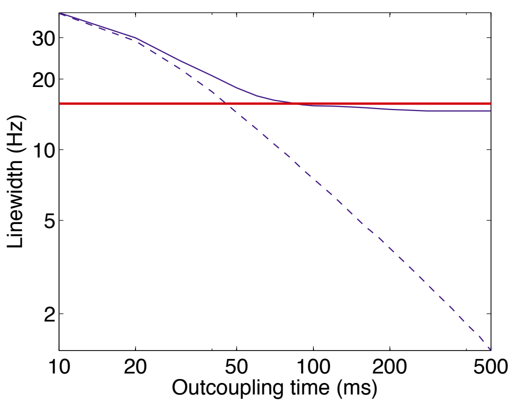

Figure 2: Atom laser linewidth for fully quantum (solid) and semiclassical (dashed) models.

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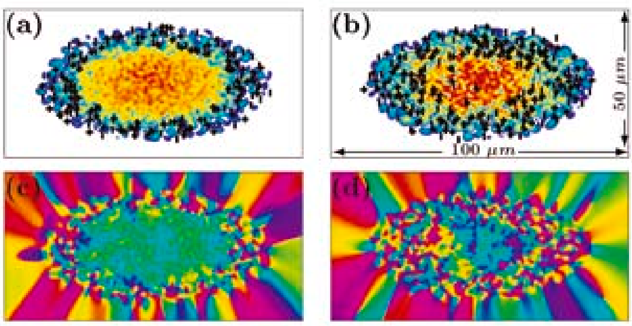
Superfluidity and thermodynamics of low-dimensional Bose gases

M. J. Davis[1], A. S. Bradley[1], C. J. Foster[1], A. G. Sykes[1], K. V. Kheruntsyan[1], P. B. Blakie[2] and T. Simula[2].
[1]*ACQAO, School of Physical Sciences, University of Queensland, Australia*
[2]*Jack Dodd Centre for Photonics and Ultra-Cold Atoms, University of Otago, New Zealand*

Degenerate Bose gas systems in one and two dimensions have many differences to standard Bose-Einstein condensates in three dimensions, and are now beginning to be realised in the laboratory [1]. It is important to be able to apply our theoretical techniques to make predictions for realistic experimental systems, or to analyze existing experimental data and interpret these results from a theoretical viewpoint.

1. Recent analytic work has suggested that quantum fluctuations in 3D BECs in an infinite system can cause a non-zero drag force on an object in a flow at all velocities [2], in contradiction with our conventional understanding of superfluidity. We are near completing a similar calculation for a one-dimensional system, which has the advantage that much of it can be done analytically. It is also feasible to numerically simulate this system, and we have begun calculations aimed at conclusively demonstrating this force in a finite system.

2. A recent experiment has made a measurement of the first-order correlation function of a 2D Bose gas that provides evidence for a superfluid Berezinskii-Kosterlitz-Thouless (BKT) phase [1]. We have been studying a size-matched homogeneous system using classical field methods in order to study the behaviour of vortex pairs, and to develop an understanding of the relationship between BEC and BKT phases in a finite-size system. We have also studied the penetration of vortices into the centre of a trapped 2D condensate (as shown in the figure below), and considered the measurement of scissor mode properties as a method to establish the existence of superfluidity [3]. Finally, we have been analyzing unpublished experimental data from NIST Gaithersburg in order to enhance the understanding of their 2D system.



(a,b) Density and (c,d) phase of a 2D trapped Bose gas at a temperature of (a,c) 114 nK and (b,d) 151 nK. The critical temperature was determined to be 155 nK. The plus and minus signs indicate vortices of positive and negative circulation, respectively. (b,d) is an example where a vortex has penetrated to the core of the gas.

3. We have established a collaboration with the van Druten group in Amsterdam who have been studying the thermodynamics of the 1D Bose gas. They have made measurements of the density profiles of their system over a range of temperatures, and we have fit these using the Yang-Yang thermodynamic solution for the 1D Bose gas in the local density approximation [4]. Their results also provide a method for accessing the momentum distribution, which cannot be computed using the Yang-Yang solution. Recently we have begun using classical field methods to try to make a connection with these results.

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Excitations and nonlocal spatial pair correlations in 1D Bose gases

A. G. Sykes[1], M. J. Davis[1], P. D. Drummond[1], D. M. Gangardt[2], K. Viering[3]
M. G. Raizen[3], and K. V. Kheruntsyan[1]
[1]*ACQAO, School of Physical Sciences, University of Queensland, Australia*
[2]*School of Physics and Astronomy, University of Birmingham, UK*
[3]*Center for Nonlinear Dynamics, The University of Texas, USA*

Physics in low-dimensional systems has long provided a rich source of fascinating and often unexpected phenomena. With the steady progress of experimental methods in ultra-cold gases, effective one-dimensional (1D) systems are beginning to be realized in the laboratory. The integrability of certain many-body problems in 1D – such as the 1D Bose gas with delta-function interactions [1] – provides an opportunity to reliably examine many-body quantum physics beyond mean-field theory. In 2007 we have made progress on several fronts in the study of 1D Bose gases.

1. We have numerically solved the equations arising from the Bethe ansatz solution for the many-body wave function, and found the excitation spectrum for a periodic finite-size system of up to 20 particles for attractive interactions and 50 particles for repulsive interations [2]. We found new analytic string solutions in the limit of infinite attractive interactions corresponding to independent solitons on the ring.

2. In collaboration with I. Bouchoule and G. V. Shlyapnikov (Universite Paris Sud IX), we have analysed the crossover transition from a fully decoherent to a (quasi)condensate regime in a harmonically trapped 1D Bose gas with weak repulsive interactions. We found explicit analytic expressions for the characteristic crossover temperature and crossover atom number. The details are given in the ACQAO Annual Report for 2006. The results have been published in Ref. [3].

3. In collaboration with M. G. Raizen's experimental group (University of Texas at Austin) and D. M. Gangardt (University of Birmingham), we have have calculated the nonlocal spatial pair correlation function for a repulsive uniform 1D Bose gas at finite temperature [4]. Our results span six different physical realms, including the weakly and strongly interacting regimes. We show explicitly that the characteristic correlation lengths are given by one of four length scales: the thermal de Broglie wavelength, the mean interparticle separation, the healing length, or the phase coherence length. In all regimes, we identify the profound role of interactions and find that under certain conditions the pair correlation may develop a global maximum at a finite interparticle separation due to the competition between repulsive interactions and thermal effects (examples are shown in Figure 1).

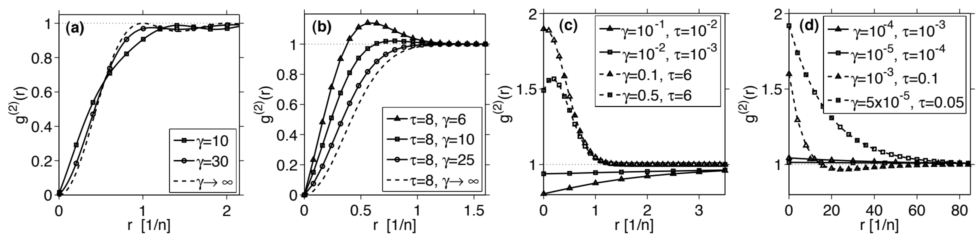

Figure 1: Pair correlation $g^{(2)}(r)$ as a function of the relative distance r (in units of $1/n$) in the following regimes: (a) strongly interacting (Tonks-Girardeau) regime, $\gamma \gg 1$, at temperatures τ below quantum degeneracy, with $\tau = 0.01$; (b) regime of high-temperature "fermionization"; (c) Solid lines – low-temperature weakly interacting gas at $\tau \ll \gamma \ll 1$, dashed lines – decoherent classical regime; (d) solid lines – weakly interacting gas at $\gamma \ll \tau \ll \sqrt{\gamma}$, dashed lines – decoherent quantum regime.

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Phase transitions and pairing signature in 1D Fermi gases

X.-W. Guan[1], M. T. Batchelor[1] and C. Lee[2]
[1] *Department of Theoretical Physics, Research School of Physical Sciences and Engineering, Australian National University, Australia*
[2] *ACQAO and Nonlinear Physics Centre, Research School of Physical Sciences and Engineering, Australian National University, Australia*

Recent achievements in manipulating cold atoms have opened up exciting possibilities for the study of many-body quantum effects in low dimensional systems. Experimental observation of superfluidity and phase separation in imbalanced Fermi atomic gases has stimulated great interest in exploring exotic quantum phases of matter with mismatched Fermi surfaces. The pairing of Fermi atoms with mismatched Fermi surfaces may lead to breached and Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states, where the bound pairs form a superfluid, while the unpaired fermions remain as a separated gas phase in momentum space. Mismatched Fermi surfaces can appear in different quantum systems, such as type II superconductors in an external magnetic field, mixtures of fermions with different internal degrees of freedom or masses, and charged neutral quark matters.

These exotic phases in the one-dimensional (1D) integrable two-component Fermi gas model have recently attracted renewed interest due to the studies of BCS-BEC crossover and quantum phase separation in a trapping potential [1, 2]. The 1D systems can be experimentally realized by applying strong transverse confinement. In the 1D interacting Fermi gas, the Fermi surface is reduced to the Fermi points. The lowest excitation destroys a bound pair close to the Fermi surface. Charge and spin propagate with different velocities due to the pairwise interaction. The external magnetic field triggers energy level crossing such that the Fermi surfaces of paired fermions and unpaired fermions vary smoothly with respect to the external field. As we demonstrated, the presence of the external field at zero temperature has an important bearing on the nature of quantum phase transitions in 1D interacting fermions.

Exact Bethe ansatz (BA) solutions provide reliable physics beyond mean field theory and also give an elegant way to analyze quantum phase transitions in the presence of an external field by means of the dressed energy formalism. We obtained exact results from this formalism for characteristics of pairing phases and quantum phase transitions in the 1D two-component strongly attractive Fermi gases [3]. We presented a systematic way to obtain the critical fields and magnetic properties at zero temperature for strongly interacting fermions. We found that the bound pairs of fermions with opposite spin states form a singlet ground state when the external field $H < H_{c1}$. A completely ferromagnetic phase without pairing occurs when the external field $H > H_{c2}$. In the region $H_{c1} < H < H_{c2}$, we observed a mixed phase in which paired and unpaired atoms coexist.

On the other hand, atomic Fermi gases with multi-internal degrees of freedom are tunable interacting many-body systems featuring novel and subtle quantum phase transitions. In contrast to the two-component fermions, three-component fermions possess new features: (1) BCS pairing can be favored by anisotropy in three different ways; (2) specifically, strongly attractive atomic fermions with three different hyperfine states can bind to form singlet trionic states. Recently, we extended our research to systems of ultracold three-component Fermi gases [4] to study the nature of trions and pairs, and calculate full ground state phase diagrams and critical fields by solving BA equations and sophisticated dressed energy equations.

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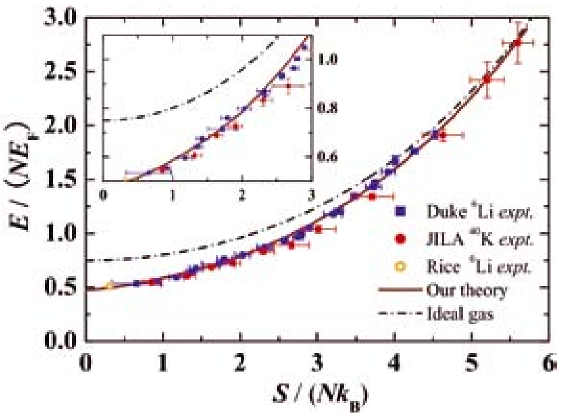
Strongly interacting Fermi gases

X.-J. Liu, H. Hu and P. D. Drummond
ACQAO, School of Physical Sciences, University of Queensland, Australia

Great progress was achieved in this very exciting field in 2007, including ACQAO's first publication in Nature Physics[1], the highest impact-factor primary research physics journal. Highlights, including three high-impact journal papers, are as follows:

First evidence of fermionic universality

A detailed comparison of theory and experiment on universal fermion thermodynamics in strongly interacting, ultra-cold Fermi gases was published in Nature Physics[1].



Measurements have confirmed a theoretical prediction published in 2006: all strongly interacting Fermi gases were predicted to show identical thermodynamic behaviour. Late in 2006, detailed experimental data became available for the first time, for different fermions under different conditions. All the new data lies on a single universal curve, exactly as we predicted. This is an outstanding discovery, showing the way to a new kind of strong-interaction physics of extreme simplicity and wide applications in other physics disciplines.

Polarized Fermi gases

Three papers in this rapidly moving new field were published, including one in the high impact Phys. Rev. Letts journal. The complete phase diagram[2] and detailed proposal for observing the exotic FFLO[3] states fora polarized 1D Fermi gas, was published, using exact solutions. Polarized Fermi gases are being experimentally studied in several laboratories.Experiments at Rice University are now underway. A mean field study for the three-dimensional phase diagram[4] was also published.

Vortices in Fermi gases

Two studies of vortices in Fermi gases were published. These are an important benchmark of superfluid behaviour, and are readily observable in experiments. One paper calculated the density profile for giant vortices[5] , the other, published in Phys. Rev. Letts., showed the existence of unique bound-states in the cores of vortices produced in polarized, strongly interacting Fermi gases[6].

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Molecular BEC of ^{6}Li$_2$

J. Fuchs, G. Veeravalli, P. Dyke, E. Kuhnle, G. Duffy, W. Rowlands, P. Hannaford and C. J. Vale
ACQAO, Swinburne University of Technology, Australia

Laser and evaporative cooling of atoms has opened the way to studies of quantum degenerate bosonic and fermionic systems. Bose-Einstein condensates of molecules and resonant superfluids, comprised of pairs of fermionic atoms, with long lifetimes can now be routinely prepared [1]. Such systems are the subject of intense investigation and may advance our understanding of other degenerate Fermi systems such as neutron stars and high temperature superconductors. In April 2007 we produced our first highly degenerate Fermi gases (DFGs) and molecular Bose-Einstein condensates (BECs) using a versatile low power crossed optical dipole trap (CDT) [2].

The starting point of our experiments is an isotopically enriched beam of fermionic ^{6}Li atoms which are Zeeman slowed and collected in a magneto-optical trap (MOT). Once around 10^8 atoms are collected in the MOT, the CDT beams, generated from an ELS VersaDisk laser (25 W, 1030 nm), are switched on and the MOT lasers are extinguished. Approximately 4×10^5 atoms are trapped in the CDT in a mixture of the $|F = 1/2, m_F = +1/2\rangle$ and $|F = 1/2, m_F = -1/2\rangle$ ground states. Next, a magnetic field close to the broad s-wave Feshbach resonance at 834 G is turned on to increase the elastic scattering length, a, between atoms in these two states so that $|a| \gtrsim 2500\, a_0$. The intensity of the CDT laser is then lowered by a factor of about 1000 over 3 seconds to achieve forced evaporative cooling. On the low field side of the resonance, where $a > 0$, a bound molecular state associated with the Feshbach resonance exists. As the temperature of the cloud drops below the binding energy of the molecular state, stable dimers are formed and remain trapped in the CDT. These molecules, consisting of two fermions, are bosonic and can undergo Bose-Einstein condensation below a critical temperature (Fig. 1a). Alternatively, on the other side of the resonance, $a < 0$, no bound molecular state exists and a strongly interacting degenerate Fermi gas is produced (Fig. 1b). These two clouds were obtained with identical experimental conditions except using different magnetic fields. The distribution of the trapped Fermi gas is broader and less dense than on the BEC side of the resonance due to Fermi pressure.

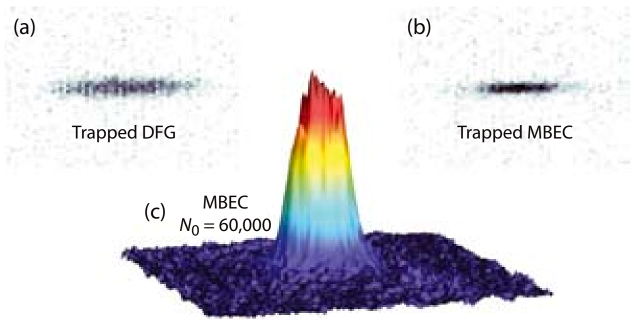

Figure 1: Absorption images of (a) a trapped degenerate Fermi gas and (b) a trapped molecular BEC. (c) A 3D plot of a near pure BEC of 60,000 molecules

We have now replaced the ELS laser with a 100 W IPG fibre laser operating at 1075 nm. We have set up a crossed optical dipole trap with the two lasers beams intersecting at an angle of $14°$, forming a cigar shaped trap with a peak depth of 2.5 mK and oscillation frequencies of 11 kHz and 1.2 kHz in the radial and axial directions, respectively. This increase in trapping power means we now collect more atoms from the MOT resulting in a larger number of atoms/molecules at degeneracy. The colour image (Fig. 1c) shows a near pure BEC of approximately 60,000 molecules prepared in this trap.

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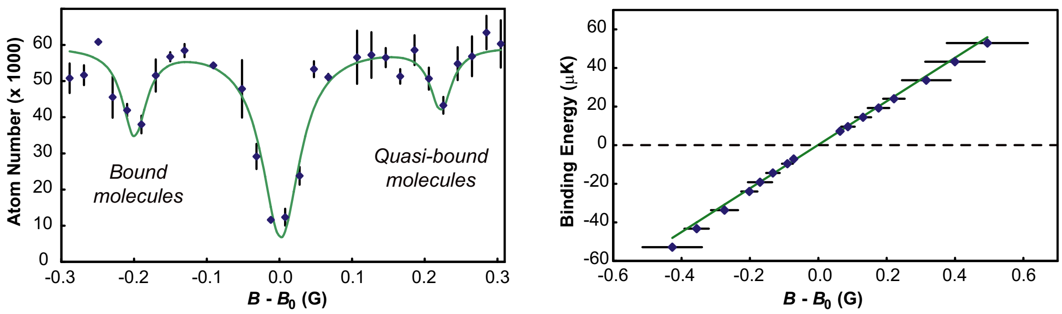
p-wave Feshbach resonances in ^{6}Li

J. Fuchs, P. Dyke, G. Veeravalli, E. Kuhnle, C. Ticknor, W. Rowlands, P. Hannaford and C. J. Vale
ACQAO, Swinburne University of Technology, Australia

The ability to control atom-atom interactions in ultracold gases is possible through magnetically tunable Feshbach resonances. These occur when the energy of two colliding atoms coincides with a bound molecular state for a different combination of internal atomic states. The scattering length diverges at the resonance, being large and positive (repulsive) below resonance where a bound molecular state exists, and large and negative (attractive) above the resonance. To date most experiments, including ours, have utilised s-wave scattering resonances for the production of molecular Bose-Einstein condensates and fermionic superfluids [1].

Feshbach resonances involving scattering with nonzero angular momentum also exist. Higher order scattering is characterised by a centrifugal barrier which usually suppresses collisions at low energy. At resonance, however, this can be overcome and strong interactions and pairing can occur. Recently, the first p-wave ($l = 1$) Feshbach molecules were produced and detected in an ultracold gas of ^{40}K [2]. Condensates of such molecules hold the promise of probing superfluidity based on pairing with higher order partial waves. A limitation for ^{40}K p-wave molecules is that dipolar relaxation limits their lifetime to a few milliseconds. In ^{6}Li there are three p-wave Feshbach resonances corresponding to the different combinations of $|F = 1/2, m_F = +1/2\rangle$ ($|1\rangle$) and $|1/2, -1/2\rangle$ ($|2\rangle$) states. One of these resonances involves two atoms in the lowest energy spin state, $|1\rangle$, and is thus not susceptible to dipolar relaxation. Hence molecules formed on this resonance have the potential to be much longer lived.

We have recently measured the binding energies of ^{6}Li p-wave molecules using radio frequency (rf) magneto-association spectroscopy for all three resonances. The binding energy increases linearly with magnetic field detuning and our measured values of $113 \pm 7\,\mu$K/G, $111 \pm 6\,\mu$K/G and $118 \pm 8\,\mu$K/G for the $|1\rangle$-$|1\rangle$, $|1\rangle$-$|2\rangle$ and $|2\rangle$-$|2\rangle$ resonances, respectively, are in good agreement with theoretical predictions. Figure 1 below shows a typical magneto-association spectrum and the measured binding energies for the $|1\rangle$-$|1\rangle$ resonance with a linear fit. We can also infer near-resonant properties of the scattering states from the measured conversion rates as a function of detuning [3].



(a) (b)

Figure 1: (a) Magneto-association spectrum showing atom loss for bound and quasibound ^{6}Li molecules (ν_{rf} = 300 kHz). (b) Binding energy of ^{6}Li p-wave molecules vs. magnetic field detuning (B_0 = 159 G).

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Quantum-atom optics using dissociation of molecular condensates

C. M. Savage[1], M. J. Davis[2], M. K. Olsen[2], J. F. Corney[2], M. Ögren[2], S. Midgley[2], and K. V. Kheruntsyan[2]

[1] *ACQAO, Department of Physics, Australian National University, Australia*

[2] *ACQAO, School of Physical Sciences, University of Queensland, Australia*

The generation and detection of strongly correlated atomic ensembles is becoming one of the central themes in the study of ultracold quantum gases. Dissociation of a Bose-Einstein condensate of molecular dimers is among the most efficient processes to produce strong pair correlations between atoms of opposite momenta.

1. We have performed first-principles quantum simulations of the dissociation of a trapped, spatially inhomogeneous Bose-Einstein condensate of molecular dimers made of bosonic atoms [1]. Using stochastic positive-P simulations we have studied spatial pair correlations of atoms produced in dissociation after time of flight. We find that the observable correlations may significantly degrade in systems with spatial inhomogeneity compared to the predictions of idealized uniform models. We show how binning of the signal can enhance the detectable correlations and lead to the violation of the classical Cauchy-Schwartz inequality and relative number squeezing. Examples of observable correlation effects via shot-noise spectroscopy of absorption images are shown in Fig. 1.

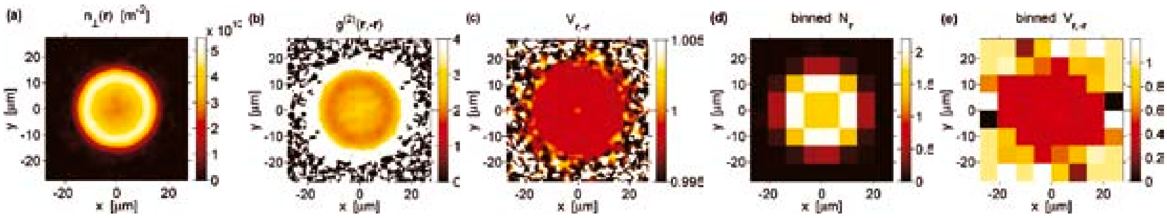

Figure 1: (a) Spatial column density of dissociated atoms $n_\perp(\mathbf{r}) = \langle \hat{n}_\perp(\mathbf{r})\rangle$. (b) Pair correlation function in the absorption image at diametrically opposite locations, $g^{(2)}(\mathbf{r}, -\mathbf{r})$. (c) Relative atom number variance $V_{\mathbf{r},-\mathbf{r}}$ at diametrically opposite locations. (d) Binned atomic signal on the detection plane, for bins of size 32×32 pixels. (e) Relative atom number variance at opposite locations after binning, showing improved squeezing below the shot noise level $V_{\mathbf{r},-\mathbf{r}} < 1$.

2. We have developed a pairing mean-field theory of dissociation of a spatially uniform BEC of molecular dimers, including both bosonic and fermionic statistics for the constituent atoms. The details are given in the ACQAO Annual Report for 2006 (p. 30), and the results have been published in Ref. [2].

3. We are currently developing alternative theoretical approaches to treat spatial inhomogeneity of the molecular condensate and to address the role of mode-mixing on the strength of atom-atom correlations. The approaches include the Hartree-Fock-Bogoliubov (HFB) theory, undepleted molecular approximation for short time dynamics in the case of fermionic atoms, and first-principle simulations using Gaussian stochastic methods [3] which should allow us to extend the first-principle stochastic simulations to multi-mode fermionic systems. The HFB approach will allow us to understand the role of atom-atom s-wave scattering interactions in the long time limit, which is not possible using the positive-P stochastic method.

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Two-component Bose-Einstein condensate on an atom chip

R. Anderson, B. V. Hall, P. Hannaford, and A. I. Sidorov
ACQAO, Swinburne University of Technology, Australia

Atom chips provide a flexible and scalable platform for applications of cold atoms and Bose-Einstein condensates (BECs) in future quantum technologies including miniaturised atomic clocks, quantum information processing and quantum sensors. Our project studies the coherent properties of a two-component BEC prepared on a magnetic film atom chip [1] using a two-photon microwave/radio-frequency transition. At a particular value 3.23 G of the magnetic field two hyperfine states $|F = 1, m_F = -1>$ and $|F = 2, m_F = 1>$ in ^{87}Rb exhibit a low differential Zeeman shift (431 Hz/G^2) and can be trapped simultaneously with long dephasing times. The coherent superposition of these two states has a long coherence time [2] and is attractive for applications in quantum atom devices.

We produce a Bose condensate of 10^5 rubidium atoms either in the $|F = 1, m_F = -1>$ state or in the $|F = 2, m_F = 2>$ state using a standard arrangement of a Z-shaped current and a bias magnetic field on the hybrid atom chip [1]. The microwave field of frequency 6.83 GHz is generated by a programmable Agilent E8257D signal generator, amplified by 40 dB and delivered to a helical antenna located outside the vacuum chamber. The radiofrequency radiation is applied to a side wire on the chip. We have characterized the coupling of RF and microwave fields to the corresponding transitions and observed Ramsey fringes in the time domain. Using RF outcoupling of the trapped $|F = 2, m_F = 2>$ BEC we observed Rabi oscillations of the atoms between five Zeeman levels of the $F = 2$ state (Fig. 1) and estimate a resonance single-photon Rabi frequency of 10 kHz. When we applied a pulse of microwave/radiofrequency fields of variable duration to the BEC in the $|F = 1, m_F = -1>$ state we observed Rabi oscillations and evaluated a two-photon Rabi frequency of 736 Hz. We applied two time-separated $\pi/2$ pulses of microwave/RF fields to a cold thermal cloud of atoms trapped in the $|F = 1, m_F = -1>$ state and observed Ramsey oscillations with a decay time of 800 ms (Fig. 2).

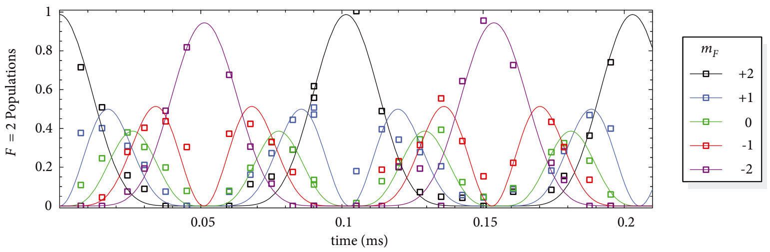

Figure 1: Rabi oscillations of BEC between five Zeeman levels of the $|F = 2>$ state. Squares are experimental results and curves are the results of numerical simulations.

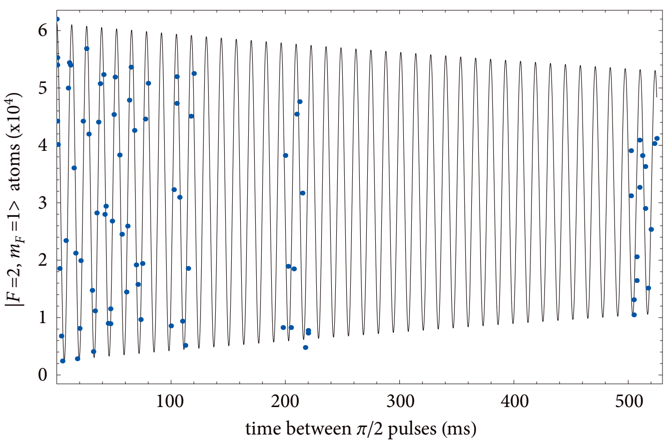

Figure 2: Ramsey oscillations of the cold atomic cloud, initially prepared in the $|F = 1, m_F = -1>$ state. The measurable signal is the population of the atoms detected in the upper $|F = 2, m_F = 1>$ state. Dots are experimental results and the curve is the fit.

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Scanning magnetoresistance microscopy of atom chips

M. Volk, S. Whitlock, C. H. Wolff, B. V. Hall and A. I. Sidorov
ACQAO, Swinburne University of Technology, Australia

Surface based geometries of microfabricated wires or patterned magnetic films can be used to magnetically trap and manipulate ultracold neutral atoms or Bose-Einstein condensates. We have investigated the magnetic properties of such atom chips using a scanning magnetoresistive (MR) microscope with high spatial resolution and high field sensitivity [1]. By comparing MR scans of a permanent magnetic atom chip to field profiles obtained using ultracold atoms [2], we show that MR sensors are ideally suited to observe small variations of the magnetic field caused by imperfections in the wires or magnetic materials which ultimately lead to fragmentation of ultracold atom clouds. Measurements are also provided for the magnetic field produced by a thin current-carrying wire with small geometric modulations along the edge. Comparisons of our measurements with a full numeric calculation of the current flow in the wire and the subsequent magnetic field show excellent agreement. Our results highlight the use of scanning MR microscopy as a convenient and powerful technique for precisely characterizing the magnetic fields produced near the surface of atom chips.

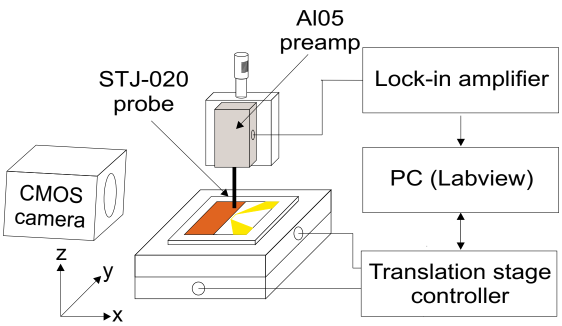

Figure 1: Schematic of the scanning magnetoresistance microscope. The sample is placed on a computer controlled $x - y$ translation stage. The magnetoresistive probe is connected to a preamplifier and the signal is filtered and digitized by a lock-in amplifier. A CMOS camera is used to determine the distance between the sensor tip and the sample.

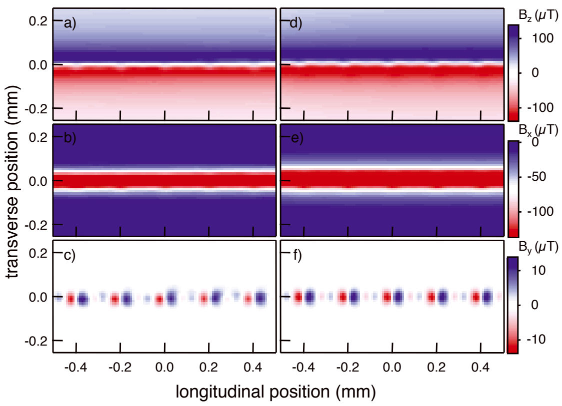

Figure 2: a to c measured out-of-plane component B_z and reconstructed in-plane components B_x, B_y of the magnetic field above the current-carrying wire atom chip. d to f corresponding results of the numerical simulation of the current distribution and the associated magnetic field, based on the geometric dimensions of the wire structure.

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Atomic four-wave mixing via condensate collisions

A. Perrin[1], C. M. Savage[2], D. Boiron[1], V. Krachmalnicoff[1], C. I. Westbrook[1], and K. V. Kheruntsyan[3]
[1] *Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Univ Paris-Sud, Campus Polytechnique, France*
[2] *ACQAO, Department of Physics, Australian National University, Australia*
[3] *ACQAO, School of Physical Sciences, University of Queensland, Australia*

We perform a theoretical analysis of atomic four-wave mixing via a collision of two Bose-Einstein condensates of metastable helium atoms. The analysis is based on first-principles quantum simulations using the positive P-representation method and is aimed at modeling recent experiments at Orsay [2]. Using the actual experimental parameters, we calculate atom-atom pair correlations within the s-wave scattering halo produced spontaneously during the collision (see Fig. 1). Our results for the strength and the width of the correlation signal are consistent with the experimental observations. We also analyze relative atom number squeezing and the violation of the classical Causchy-Schwartz inequality.

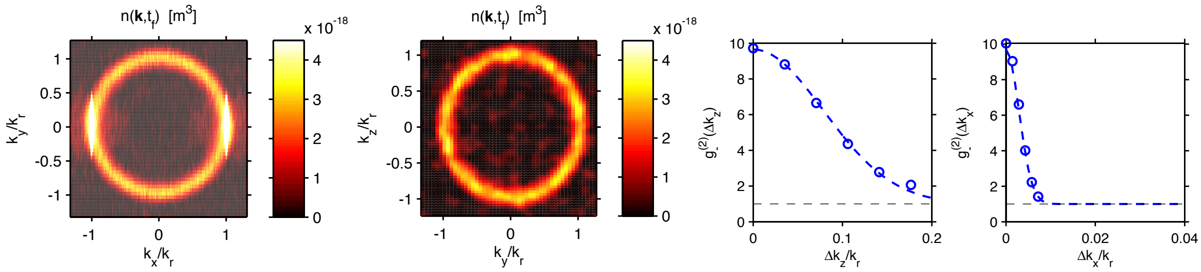

Figure 1: First and second panels: slices through $k_z = 0$ and $k_x = 0$ of the 3D atomic density distribution in momentum space $n(\mathbf{k}, t_f)$ after $t_f = 25\ \mu$s collision time. The scale is chosen to show the s-wave sphere of spontaneously scattered atoms and cuts off the colliding condensates (shown in white on the first panel) containing initially 10^5 atoms. Third and fourth panels: pair correlation of atoms on the opposite sides of the sphere as a function of the relative offset Δk_i, in units of the collision momentum k_r. The dots are the numerically calculated values; the dashed lines are simple Gaussian fits $\propto 1 + 9.7 \exp(k_i^2/2\sigma_i^2)$ to guide the eye, with $\sigma_z = 0.0785k_r$ and $\sigma_x = 0.0029k_r$.

Quantum dynamical simulations of this scale, i.e., corresponding to ensembles of large numbers of interacting particles in realistic parameter regimes, are becoming possible due to the advances in computational power and improvements in numerical algorithms (for recent examples, see Refs. [3, 4]). The importance of the present example with metastable helium is that the quantum correlations of interest have been both measured experimentally and calculated theoretically. In this sense, this work represents one of the first examples where the results of experimental measurements can be scrutinized to the level of *quantitative* theoretical understanding using first principles calculations. Our results can also serve as benchmarks for approximate theoretical methods to establish the range of their validity.

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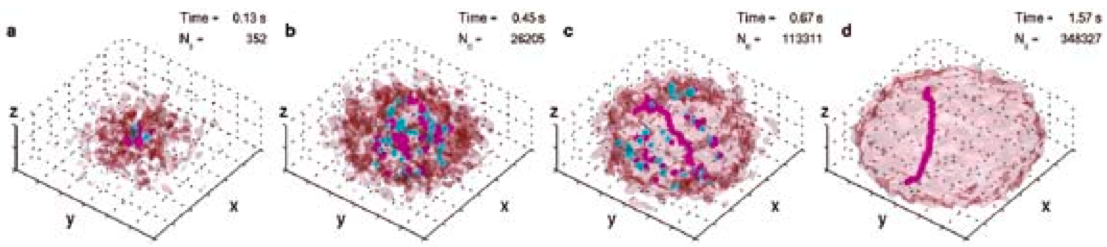
Classical field simulations of thermal Bose-Einstein condensates

M. J. Davis[1], A. S. Bradley[1], G. M. Lee[1] and C. W. Gardiner[2]
[1]*ACQAO, School of Physical Sciences, University of Queensland, Australia*
[2]*Jack Dodd Centre for Photonics and Ultra-Cold Atoms, University of Otago, New Zealand*

The aim of this project is to continue to develop and apply methods for describing the dynamics of Bose-Einstein condensates at finite temperature. The techniques being utilised are approximate; however they are aimed at performing non-perturbative calculations for realistic experimental systems. A focus for 2007 has been the dynamics of condensate formation using the stochastic Gross-Pitaevskii formalism [1]. Beginning from slightly above the critical temperature, we assume an instaneous quench of the thermal cloud and study the resulting condensation dynamics.

Firstly, we have studied rapidly rotating systems in two-dimensions. In contrast to stirring a vortex-free condensate, where topological constraints require that vortices enter from the edge of the condensate, we find that phase defects in the initial non-condensed cloud are trapped en masse in the emerging condensate. Bose-stimulated condensate growth results in a disordered vortex configuration. At sufficiently low temperature the vortices then order into a regular Abrikosov lattice in thermal equilibrium with the rotating cloud. We determined the effect of thermal fluctuations on vortex ordering in the final gas at different temperatures, and found that the BEC transition is accompanied by lattice melting associated with diminishing long range correlations between vortices across the system [2].

Secondly, we have studied condensate formation in a three-dimensional system for parameters matching the experimental conditions in the Anderson lab at the University of Arizona. We have made the exciting observation that in a significant fraction of simulations a vortex is observed to be trapped in the condensate as it grows. We have made comparisons with the available experimental data, and find excellent quantitative agreement. An example of condensate formation where a vortes is trapped is shown in the figure below, and a joint theoretical and experimental paper is in preparation.



An example of the formation of a Bose-Einstein condensate in a 3D harmonic trap where a vortex is spontaneously trapped. Each plot (a–d) shows an isodensity surface at the time indicated, and the magenta (cyan) lines indiate where positive (negative) 2π phase windings have been identified in the atomic field. The condensate number is determined using the Penrose-Onsager criterion over 300 simulations.

Finally, we have continued with work on a 1D model of a continuously pumped atom laser using a stochastic Gross-Pitaevskii model. In this description the condensate is continuously replenished from a thermal atomic reservoir using a realistic growth scenario, and the atom laser beam is generated from this by Raman outcoupling. The project focuses on the properties of the output beam and will provide realistic estimates of the linewidth and coherence limitations of a cw atom laser at finite temperature.

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Precision measurements using ultracold metastable helium

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

The ultracold atomic sample created in the metastable helium (He*) BEC experiment is an ideal testbed for performing atomic physics experiments in a controlled environment on this, the simplest of multi-electron atoms. We have used this apparatus to determine for the first time the $2\,^3P_1 - 1\,^1S_0$ transition rate [1].

The experiment exploits the very long (∼1 minute) confinement times obtained for atoms magneto-optically trapped in an apparatus used to create a Bose-Einstein condensate of metastable ($2\,^3S_1$) helium. The $2\,^3P_1 - 1\,^1S_0$ transition rate is measured directly from the decay rate of the cold atomic cloud following 1083 nm laser excitation from the $2\,^3S_1$ to the $2\,^3P_1$ state, and from accurate knowledge of the $2\,^3P_1$ population.

The decay rate measurement is performed in a relatively unperturbed environment by releasing the atoms momentarily from the trap. This is achieved by turning off the $2\,^3P_2 - 2\,^3S_1$ trapping laser (P2 light) and briefly irradiating the slowly expanding cloud with a laser tuned near the $2\,^3S_1 - 2\,^3P_1$ transition (P1 light). The presence of the P1 light continually replenishes the $2\,^3P_1$ population from the $2\,^3S_1$ state, thereby ensuring that the $2\,^3P_1 - 1\,^1S_0$ decay rate dominates the decay rate due to the otherwise much faster $2\,^3P_1 - 2\,^3S_1$ transition.

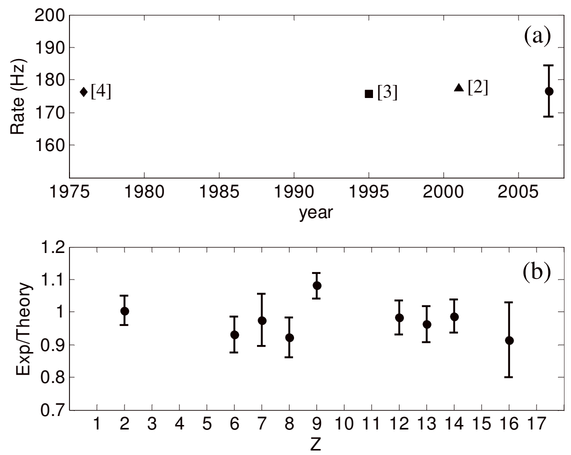

Figure 1:(a) Historical progress of theoretical determinations for the helium $2\,^3P_1 - 1\,^1S_0$ decay rate, together with the experimental value (and uncertainty) from the present work. (b) Ratio of the experimental to the most recent theoretical decay rates, along with experimental uncertainties, for the $2\,^3P_1 - 1\,^1S_0$ transition in the heliumlike isoelectronic sequence.

To determine the P1 population the trap light is extinguished momentarily, and a pulse of P1 light briefly saturates the ensemble following an interrogation pulse below saturation. The P1 population is then derived from the ratio of the fluorescence signals.

The value obtained for the decay rate is 177±8 s^{-1}, which agrees very well with theoretical predictions, the most recent value being 177.6 s^{-1} [2] (Figure 1a). This accuracy compares favorably with measurements for the same transition in heliumlike ions higher in the isoelectronic sequence (Figure 1b). The value for the helium decay rate is the only value for Z<6 and anchors the isoelectronic sequence for this transition.

A similar situation pertains to the $2\,^3P_2 - 1\,^1S_0$ transition for which there is no helium measurement, and for the $2\,^3S_1 - 1\,^1S_0$ transition where the only helium measurement has a very large uncertainty. The determination of these transition rates is the subject of future investigations in this laboratory.

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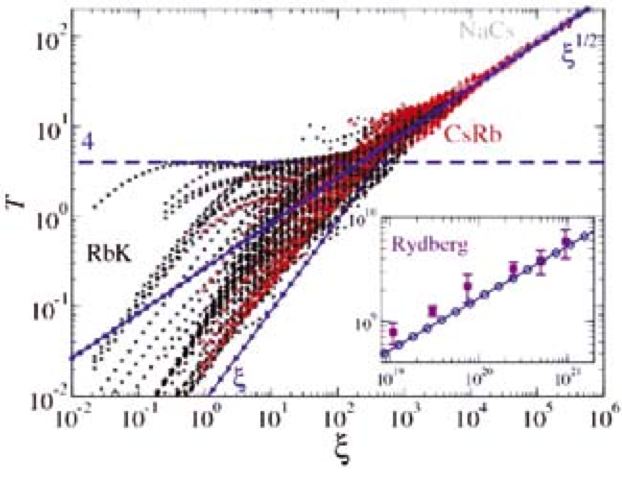
Universal dipolar scattering

C. Ticknor
ACQAO and CAOUS, Swinburne University of Technology, Australia

When polarised by an external electric field the scattering of polar molecules is dictated by their dipole-dipole interaction. The characteristic length and energy of a dipolar system are defined in terms of mass m and the induced dipole moment d, and they are $D = md^2/\hbar^2$ and $E_D = d^2/D^3 = \hbar^6/m^3d^4$, respectively. With the scattering energy, we form a dimensionless quantity $\xi = E/E_D = m^3d^4E/\hbar^6$ which parametrizes the scattering. If one rescales the multi-channel radial Schrödinger equation using the length scale D, one finds the only free parameter is ξ. This suggests universal scaling of dipolar scattering. To illustrate this behaviour we have compiled scattering data from many different molecular systems for a variety of conditions. In the figure we have plotted $\mathcal{T}$, ($\sigma = \frac{2\pi}{k^2}\mathcal{T}$), as a function of ξ for many different polar molecules. The figure shows the transition in the scattering from highly variable at low ξ, where the scattering depends on short range, to uniform at large ξ. This transition of $\mathcal{T}$ signifies the onset of universal dipolar behaviour. This will occur when the dipolar interaction is dominant and the scattering will be insensitive to the short range interaction. For this reason different molecules, even bosons and fermions, have the same scattering behaviour. The details are in Ref. [1, 2].

For large ξ, dipolar systems obey a universal scaling, where all scattering dipoles will behave similarly irrespective of the details of the short range. A striking example of this theory being applied is an experimental measurement of the cross section for resonant collisions of Rydberg atoms [3]. In this experiment two identical Rydberg atoms in the ns state, where n (s) is the principal quantum number (orbital angular momentum), are resonantly scattered into a degenerate threshold to which it is coupled via the dipole-dipole interaction. This system has huge dipole moments, $d \propto n^2$, e.g., consider $n = 22$, the dipole moment is about 100 D! Typical molecular dipole moments are 1D. Numerically converging this calculation would be impossible with the present computational techniques, but using the scaling presented here we can obtain an accurate estimate of the total cross section, see the figure inset.



The transition of dipolar scattering to a universal behavior is shown by plotting $\mathcal{T}$ vs ξ for many polar molecules. The molecules are ^{87}Rb^{41}K (black x), fermionic ^{87}Rb^{40}K (black +), NaCs (brown square), and RbCs (red ◇) with many different scattering conditions. The inset is the experimental cross section for scattering Rydberg atoms from Ref. [3] with the scaling.

With the growing importance of cold polar molecules, with possibilities such as quantum computing, tests of the standard model, and novel many body physics, accurate and yet simple theories to understand their collisions will be important. We have studied the scattering and find an accurate scaling of quantum mechanical dipolar scattering. The universal scattering regime will be readily achieved in polar molecule experiments. Consider collisions of RbCs and NaCs at a temperature of 500nK with a modest field of 5kV/cm; ξ is 230 and 14570, respectively. Both are in the universal dipolar regime.

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Demonstration of spatial entanglement

K. Wagner, J. Janousek, H. Zou, V. Delaubert, S. Pereira, C. C. Harb,
N. Treps, P. K. Lam and H.-A. Bachor
ACQAO, Department of Physics, Australian National University, Australia

We have demonstrated the entanglement of the spatial properties (position and direction) of two laser beams. This is the first time optical multimode entanglement has been created and it a very clear demonstration of the original ideas of Einstein, Podolsky and Rosen, applied to the position and momentum of continuous laser beams. We have achieved this result by combining a TEM00 reference beam with a squeezed TEM10 squeezed beam, and then entangling this beam with another TEM10 squeezed beam [1]. Measurement of the real part of the two TEM10 components of the entangled beams then shows the position of the beams, and the imaginary parts show the transverse beam momentum.

A direct comparison of the correlations between the two beams allows us to calculate the degree of inseparability. The two beams are entangled if these correlations are stronger than can be attained by classical means. EPR entanglement is measured by making predictions on what will be measured on one beam, based on a measurement of the other beam. We measure the differential position and momentum and demonstrate that our beams have fluctuations in these two properties below the quantum noise limit (QNL), as shown in the central part of Figure 1. We have measured a degree of inseparability of 0.51, and a degree of EPR paradox [2] of 0.62.

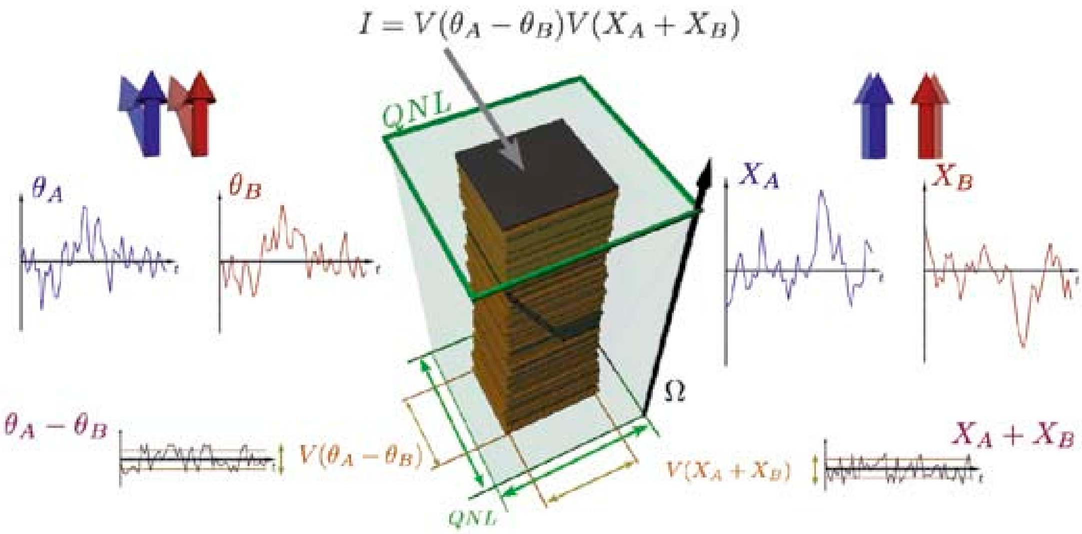

Figure 1: Each entangled beams position (left) and direction (right) is above the QNL. But when we measure the differential position and direction, we can see that these two properties are below the QNL, as seen by the variances $V(X_A + X_B)(\Omega)$ and $V(\theta_A - \theta_B)(\Omega)$. The product $V(X_A + X_B)(\Omega)V(\theta_A - \theta_B)(\Omega)$ gives the degree of inseparability, shown as the area the square in each slice of the central tower.

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Quantum information

M. D. Reid, E. G. Cavalcanti, T. Vaughan, C. Foster and P. D. Drummond
ACQAO, School of Physical Sciences, University of Queensland, Australia

In 2007 ACQAO has developed new, unambiguous approaches to test for the fundamental quantum concepts of: position measurement[1], Einstein-Podolsky-Rosen (EPR)[2], and Bell[3], correlations. These new approaches, meriting a high impact Physical Review Letter, can be used for developing novel types of sensors or other quantum technologies.

Center of mass measurements

We have developed a concrete approach to treat the quantum limits to center of mass measurements[1]. We show that, for the same density an N-particle fermionic cluster can be measured with up to N times lower variance than a bosonic cluster of quantum particles. This indicates that ultra-cold Fermi gases may be useful as gravity or magnetic sensors, due to the strongly correlated nature of the fermions.

Signatures of macroscopic EPR entanglement

In fundamental quantum physics, macroscopic entanglement is a new and untested area of physics. This work will lead to novel EPR experiments [2, 3], taking into account inefficient detctors and macroscopic particle numbers of interest in quantum-atom optics. These new quantum limits and unambiguous EPR entanglement measures are within reach of current generation and detector technologies in quantum-atom optics. They also have many potential applications in areas of new technology.

Continuous variable tests of Bell's theorem

The original Bell inequality, and all of its generalizations, have so far been applicable only to the case of discrete or binned observables. We have developed the first continuous variable *correlation* tests of Bell inequality[3]. Violation of these new inequalities is predicted for multiparticle quantum states, the GHZ states, generated using multiple parametric down conversion. This gives potential for the efficiency loop-hole to be closed for Bell's theorem, because of the high efficiencies possible for quadrature phase amplitude detection. The detection efficiencies required are practical even for very large particle numbers n, for which *the discrepancy between the quantum and classical result actually increases.*

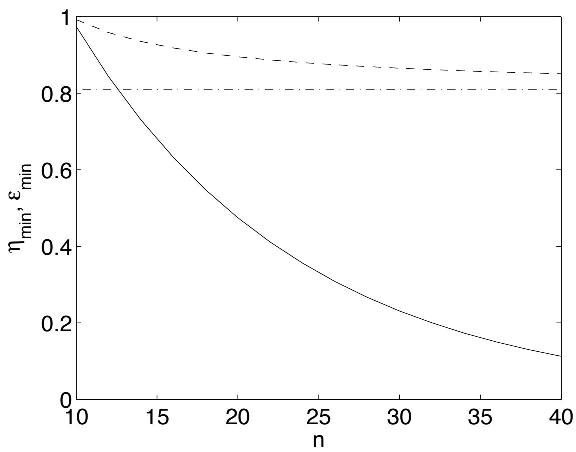

Figure on left: Minimum state preparation fidelity ϵ_{min} for ideal detectors (solid line), and minimum detection efficiency η_{min} for ideal state preparation (dashed line) required for violation of the continuous variable Bell inequality as a function of the number n of modes/sites present. The asymptotic value of η_{min} is the dash-dotted line, $\eta = 0.8$.

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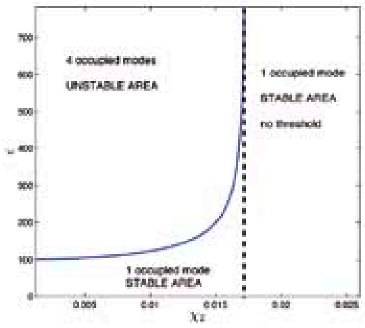
Optical CV quantum information

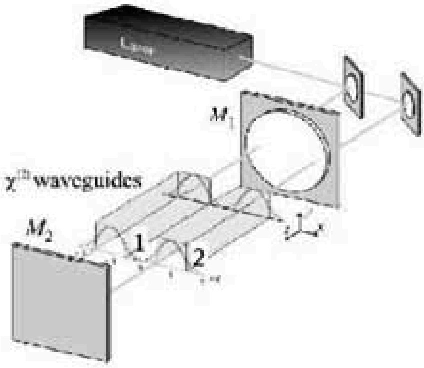
M. K. Olsen, A. S. Bradley, M. D. Reid, M. J. Mallon and C. Pennarun
ACQAO, School of Physical Sciences, University of Queensland, Australia

We have continued with this research, studying entanglement and states which exhibit the Einstein-Podolsky-Rosen (EPR) paradox, both central to quantum mechanics [1]. We have investigated both bipartite and tripartite entanglement, publishing an overview of our previous work [2]. The new systems we have investigated are combined downconversion and sum frequency generation [3], the quantum optical dimer [4], and sum frequency generation [5]. We have continued our collaborations with the experimental group of Olivier Pfister in the USA and one of us gave a lecture course at the Università dell'Insubria in Italy as part of their distinguished visiting professor program.



The first process [3] exhibits previously unknown stability properties and has three distinct operating regimes. There are three outputs, with the χ_1 nonlinearity responsible for downconversion of ω_0 pump photons to ω_1 and ω_3 and χ_2 combining ω_3 with ω_0 to produce ω_2. The figure shows the stability properties with $\chi_1 = 0.01$, cavity loss rates $\gamma_0 = \gamma_1 = \gamma_3 = 1$, and $\gamma_2 = 3$, as χ_2 and the pump amplitude are varied. The dashed line separates the regimes with and without threshold. We found that this system does produce tripartite entanglement, but in an asymmetric way.

The quantum optical dimer consists of two evanescently coupled nonlinear media inside a Fabry-Perot, as shown in the figure below.



In our work on this we showed that a demonstration of the EPR paradox is equal to a demonstration of bipartite entanglement. The cavities are pumped at a fundamental frequency and light at the harmonic frequency is produced by the nonlinear media. Under the appropriate conditions, bipartite entanglement at both frequencies is produced. This system has the advantages that it is modular and can be tuned by varying the cavity detunings, mirror losses and pumping rates. It may therefore be a good candidate, along with other nonlinear couplers, for the exhibition of asymmetric steering [6].

We have analysed sum frequency generation in terms of its ability to entangle modes at very different frequencies, which may have applications in quantum communication and teleportation. We found that, even though this process is used in many applications, very little was known about the quantum properties once it is enclosed in an optical cavity. We discovered that there is a threshhold above which nondegenerate downconversion becomes the dominant process, and that this system can also exhibit asymmetric steering.

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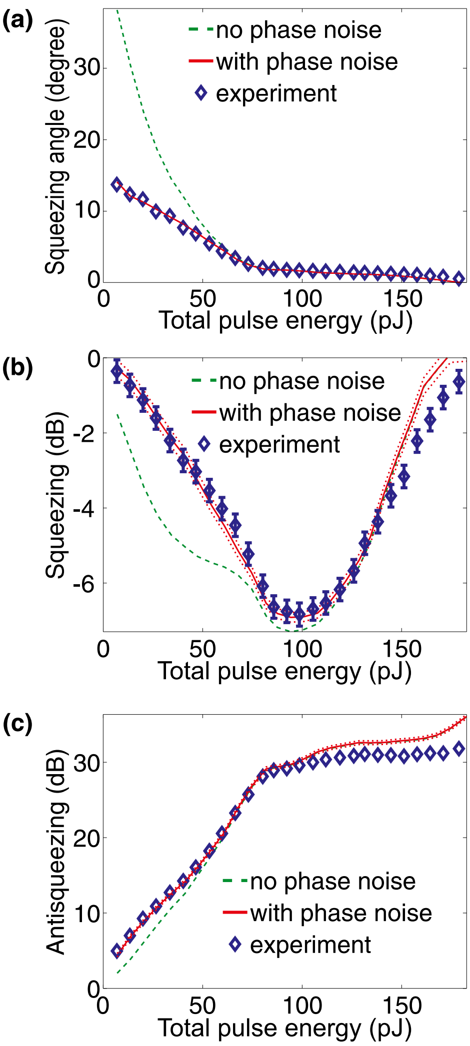
Raman-induced limits to efficient squeezing in optical fibres

J. F. Corney[1], P. D. Drummond[1], R. Dong[2], J. Heersink[2], U. L. Andersen[2,3] and G. Leuchs[2]
[1] *ACQAO, School of Physical Sciences, University of Queensland, Australia*
[2] *Institut für Optik, Information und Photonik, Universität Erlangen–Nürnberg, Germany*
[3] *Department of Physics, Technical University of Denmark, Denmark*

We report new experimental measurements and quantum simulations of polarization squeezing using ultrashort (FWHM 140 fs) photonic pulses in a single pass of a birefringent fiber. We measure what is to our knowledge a record squeezing of -6.8 $\pm$ 0.3 dB in optical fibres, which when corrected for linear losses is -10.4 $\pm$ 0.8 dB. The measured polarization squeezing as a function of optical pulse energy, spanning a wide range from 3.5-178.8 pJ, shows very good agreement with the quantum simulations. Furthermore, the experiments confirm the theoretical prediction that Raman effects limit and reduce squeezing at high pulse energy [1].



Experimental and simulation results for the (a) squeezing angle, (b) squeezing and (c) antisqueezing for a 13.2m fibre are plotted in the figure as functions of the pulse energy. Error bars on the squeezing data indicate the uncertainty in the noise measurement; for the antisqueezing, the error bars were too small to be plotted. Dotted lines indicate the sampling error in the simulation results.

The quantum dynamics of radiation propagating in a single-mode optical fibre were simulated using a truncated Wigner phase-space method[2]. The simulations included the effects of dispersion up to the third order and the $\chi^{(3)}$ nonlinearity as well as the Raman coupling to thermal phonons. The Raman fraction of the nonlinearity is estimated as 15% and the photon number ($2\bar{n}$) in a fundamental soliton pulse as 4.5 $\times$ 10^8. The excess phase noise, such as depolarizing guided acoustic wave Brillouin scattering (GAWBS)[3], is estimated by fitting the simulated squeezing angles to the experimentally measured squeezing angles as shown by red solid line in Fig. (a). After taking the 13% linear loss into account, the theoretical results for squeezing and antisqueezing which are given in the Fig. (b) and (c) by red solid lines achieve a very good match with the experimental results. The effect of the GAWBS is seen to be a reduction in squeezing for lower pulse energies.

As the optical energy goes beyond 98.6 pJ, the squeezing is reduced, eventually reaching the shot noise limit (SNL), and the increment of antisqueezing slows down to a plateau area. Above the soliton energy ($\approx$120 pJ), the deterioration of squeezing is attributed to the Raman effects since this deterioration does not appear in simulations with only electronic nonlinearity and dispersive effects; in addition, the third-order dispersion (TOD) has a noticeable effect on the squeezing at high energies.

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Broadband optical delay with large dynamic range

M. R. Vanner, R. J. McLean, P. Hannaford and A. M. Akulshin
ACQAO, Swinburne University of Technology, Australia

The use of atomic media to produce optical delay has predominantly exploited the steep dispersion associated with electromagnetically induced transparency (EIT) [1]. While this can lead to very low group velocities it has a severe bandwidth limitation owing to the narrow spectral range over which the transparency and steep dispersion occur, making delays longer than the pulse width difficult to obtain.

An attractive approach to realising a wide-bandwidth delay line utilises the intrinsic positive dispersion and high transmission between two absorption lines in an atomic vapour [2]. We have explored the delay and transmission properties of optical pulses tuned between the ^{85}Rb (F=2) and ^{87}Rb (F=1) components of the Rb D2 line, separated by about 2.5 GHz [3]. The observed optical delays for pulses at the frequency of peak transmission are shown in Fig 1a) for temperatures between 105°C and 135°C. A fractional delay (delay relative to pulse width) of 4.3 was observed for a transmission of 9% with good pulse shape preservation. The fractional delay is limited in these experiments by the pulse duration we are able to generate.

While temperature tuning provides coarse but slow tuning of the delay, we have been able to demonstrate rapid control using hyperfine optical pumping. Because the pulses are tuned between absorption resonances from different isotopes, an optical pumping laser tuned to the (F=1) or (F=2) ^{87}Rb component of the D1 line respectively reduces or increases the population of ^{87}Rb (F=1) ground state atoms interacting with the signal pulse, and hence the dispersion. In this manner, the delay at 110°C was reduced by approximately 17.5% or increased by 25% of the unmodified delay (Fig 1b).

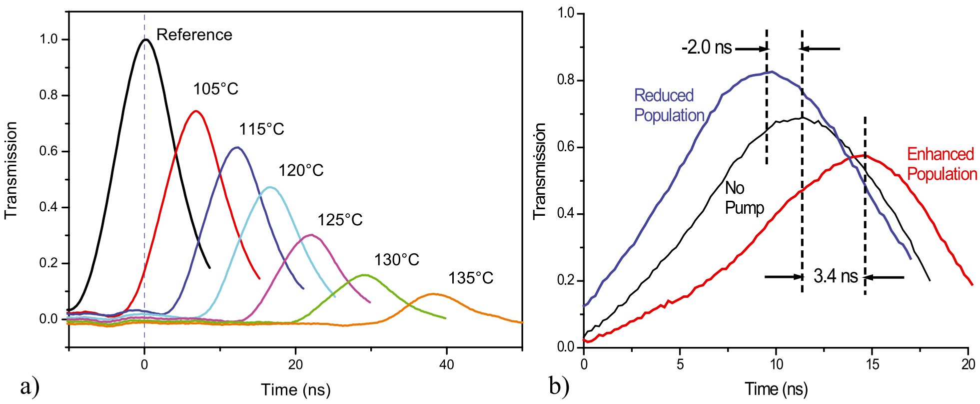

Figure 1: a) Delayed pulses with increasing temperature. b) Reduced and increased delay by optical pumping that reduces or enhances the population of the ^{87}Rb (F=1) ground state.

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Quantum memory using Gradient Echo and EIT

G. Hétet[1], M. Hsu[1], B. C. Buchler[1], P. K. Lam[1], J. J. Longdell[2], A. L. Alexander[3] and M. J. Sellars[3]
[1]*ACQAO, Department of Physics, The Australian National University, Australia*
[2]*Department of Physics, University of Otago, New Zealand*
[3]*Laser Physics Centre, Research School of Physical Sciences and Engineering, Australian National University, Australia*

We have investigated two quantum memory schemes, the Gradient Echo Memory (GEM) and Electromagnetically Induced Transparency (EIT). In the GEM scheme [1], light is stored in an ensemble of two-level atoms of long excited state decay time. By applying an external electric field, the energy levels of the atoms may be Stark shifted, providing a linear frequency shift along the storage medium. An incoming light pulse will then be absorbed, with each frequency component of the optical signal frozen in a different point along the storage medium. Upon inversion of the Stark shift, the dipoles reverse their evolution and rephase, causing the light to be re-emitted in the forward direction. This process is depicted in Figs. (a) to (c). Figure (d) shows the real part of the optical field as it enters the GEM system (top left) and then decays as it is stored in the optical coherence of the atoms. In the centre of the simulation, the Stark shift is reversed causing the optical field to gain strength and speed as leaves the storage medium. Our modelling has shown that this memory can be ideally efficient and can preserve the quantum state of the optical field without adding any extra quantum noise. Experiments with classical light pulses have demonstrated light storage using GEM [1].

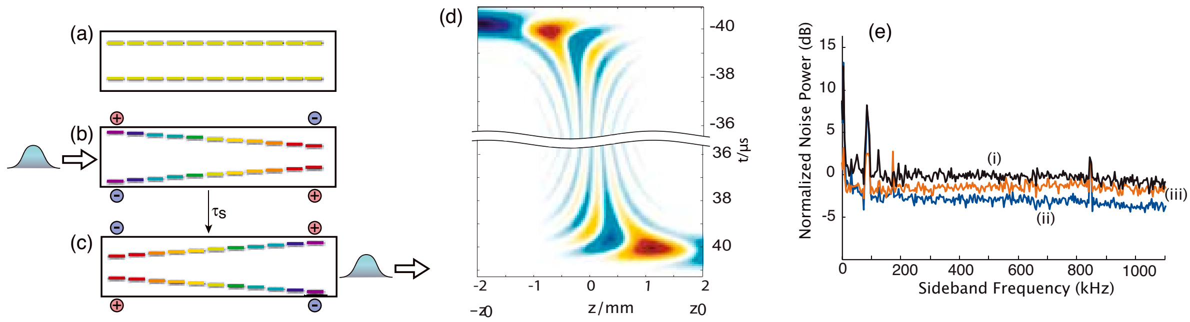

Figure 1: (a) An ensemble of two-level atoms used for GEM. (b) The Stark shifted atoms absorb all frequency components of a light pulse. (c) The reversal of the Stark shift releases the light. (d) The real part of the optical field as it is stored in the GEM. (e) Storage of squeezed light in EIT: (i) shot noise, (ii) squeezing after EIT and (iii) squeezing before EIT.

Our EIT work is both theoretical and experimental. Numerical and analytic quantum models of EIT have been used to investigate how well it performs as an optical quantum memory [2]. The modelling includes sources of quantum noise that degrade the performance of EIT. Any non-ideal system needs some criteria with which it may be characterised. To this end, we have proposed the use of quantum information criteria to quantify the performance of EIT. Experimentally, we have worked on the storage of squeezed states of light. Using the source of tuneable squeezed light developed in our labs [3], we have so far demonstrated a 2.2 μs delay of a squeezed state. Preliminary results are shown in Figure (e). Here, an initial squeezed state (iii) emerges still squeezed (ii) after transmission.

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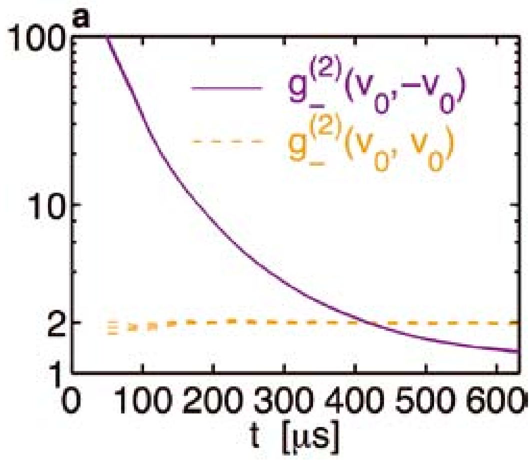
Quantum dynamics in many-body systems

J. Hedditch, J. F. Corney, T. G. Vaughan, S. Hoffmann, D. Barry and P. D. Drummond
ACQAO, School of Physical Sciences, University of Queensland, Australia

Techniques for quantum simulations were developed further and applied to very large systems in 2007, including a hybrid approach suitable for quantum Brownian motion, and novel techniques for spin systems. The Gaussian phase-space method developed at ACQAO[1, 2, 3], was recently highlighted by a Japanese computational physics team[4] in a paper on the relevance of the well-known Hubbard model for high-Tc superconductivity. Using the method, they were able to explore previously intractable regions of the strongly interacting Hubbard model with any approximation or sign-error.

BEC collision with 150,000 atoms from first principles

The collision of pure ^{23}Na BECs, as in a recent experiment at MIT, represents a superb opportunity for observational tests of first-principles quantum dynamical simulations. In these simulations[5], a 1.5×10^6 atom BEC is divided into two halves with opposite velocities, which then collide freely. The dynamics of the correlations between the scattered atoms are shown below:



The figure to the left shows the extremely strong quantum correlations predicted between atoms with opposite velocity (solid line), and thermal correlations between scattered atoms at the same velocity (dashed). **This is the first exact quantum dynamical simulation of colliding BECs.** Measurable results similar to that predicted by this model have been seen experimentally. Our model treats $2^{600,000}$ quantum states, or $600,000$ qubits. The resulting paper was published in Physical Review Letters in 2007[5], and awarded a rare **Editor's suggestion.**

XMS simulation code

XMDS, a novel code generator program, is used for quantum dynamical simulations. An extensive rewriting of this program was carried out, with a view to creating a much shorter, easily modified and more efficient code generator, with a modular library for different applications, easily modified by end-users. To deal with end-user requirements, development was extended to a code-generator with a much simpler yet more powerful simuation language, called XMS. The new code-generator is written in the high-level Python language. Although any output computer language is possible, the initial development has focused on the powerful FORTRAN 90 language, due to its extensive array-handling ability. This was successfully implemented, and is now in the testing and documentation phase.

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Quantum effects and entanglement in Bose-Einstein condensates

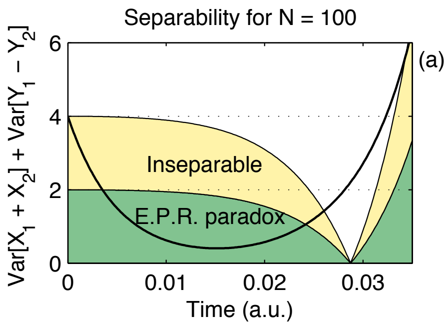
M. J. Davis, A. S. Bradley, M. K. Olsen, A. J. Ferris, S. Wüster and B. J. Dąbrowska-Wüster
ACQAO, School of Physical Sciences, University of Queensland, Australia

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

1. We have identified that the reduction in density fluctuations due to interactions in a Bose-Einstein condensate at zero temperature implies that there is relative number squeezing between the left and right hand sides of the system. We have performed calculations of this using Bogoliubov theory, and also studied how this is affected by time-of-flight expansion and imaging. The ANU He BEC experiment has provided us with a set of data that is being analyzed to determine if this is experimentally observable. Related to this, we have begun work with the Obethaler group at the University of Heidelberg on calculating the theoretical relative number squeezing that they would expect in their double-well BEC experiment as a function of temperature and barrier height.

3. We have been interested in the effect of quantum noise in the collapse of Bose-Einstein condensates as the interaction strength is manipulated with a Feshbach resonance from positive to negative. A paper on quantum effects in the Bosenova was published at the start of the year [2], and we are now studying an experiment that observed the formation of 3D solitons after a collapse [3]. We have found that although these solitons appear to be repulsive, this has more to do with the effects of quantum noise rather than the relative phase of the components.

4. We have continued studying degenerate four-wave mixing of a BEC in a moving 1D optical lattice, where atoms from a mother condensate form two entangled daughter condensates with differing momenta. A simplified three-mode model showed that significant continuous variable entanglement could be generated [4], and we have extended this to an inhomogenous multimode model. In order to prove entanglement between atomic beams, we need to be able to make phase-sensitive homodyne measurements of the atomic fields. We have adapted criteria used in quantum optics and shown how their usage is slightly different with atoms as in the figure to the right. This is largely due to the difficulty in obtaining a phase reference condensate many orders of magnitude larger than that which is being measured.



Adapted Duan and EPR measurements for a three-mode model of four wave mixing in an optical lattice. The yellow shaded area shows where the two modes are inseparable and the green shaded area shows the limits for demonstration of the EPR paradox.

5. We have analysed an experiment performed in Utrecht [5] which exhibited superradiant scattering of laser light from a Bose-Einstein condensate, and which potentially can generate entanglement between light and atoms.

6. Finally, our work on dynamical instabilities in a BEC in an optical lattice was published [6].

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Spinor matter waves: Modulational instability vs. nonlinearity

B. J. Dąbrowska-Wüster[1], E. A. Ostrovskaya[1], T. J. Alexander[1], Yu. S. Kivshar[1], E. V. Doktorov[2] and V. M. Rothos[3]

[1] *ACQAO and Nonlinear Physics Centre, Research School of Physical Sciences and Engineering, Australian National University, Australia*

[2] *B.I. Stepanov Institute of Physics, Belarus*

[3] *Aristotle University of Thessaloniki, Greece*

In the recent years there has been a growing interest in the dynamics of spin-1 Bose-Einstein condensate composed of atoms in three different hyperfine states $m_F = 0, \pm 1$ and trapped in an optical dipole trap or an optical lattice. The rich dynamics of the spinor matter waves, which includes domain separation, formation of spatial patterns and three-component localized states is partly due to the dynamical (modulational) instabilities that occur in this nonlinear system with complex intra- and inter-component interactions. It is therefore of critical importance to understand details of the interplay between the instabilities and the effect of nonlinearity.

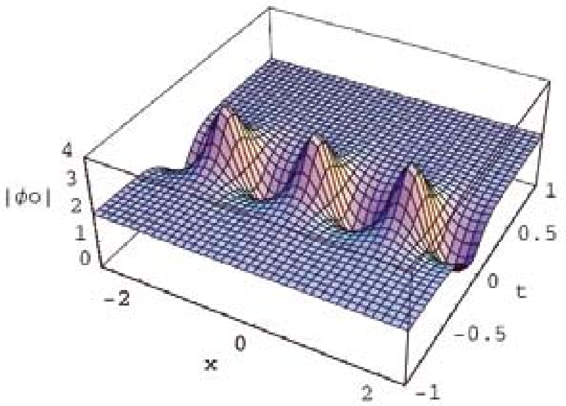

Figure 1: Time evolution of the density of the $m_F = 0$ spinor-component in a lattice-free, quasi-1D sigar-shaped trap. The densities of the $m_F = \pm 1$ components oscillate in phase with the $m_F = 0$ component.

To investigate the details of the spinor dynamics beyond the onset of modulational instability, we have considered a mean-field model of a ferromagnetic spinor condensate with attractive interactions confined in a quasi-1D sigar-shaped trap. Under certain assumptions, this model can be reduced to a fully integrable matrix Nonlinear Schrödinger equation [1], which lends itself to a fully analytical analysis. Our study revealed that the exponential growth of small-amplitude perturbations due to the modulational instability of a spinor condensate is halted by the emergence of the nonlinearly localized structures and replaced by an exponential decay. The overall evolution therefore demonstrates the Fermi-Pasta-Ulam-like recurrence pattern (see Fig. 1) where the phase trajectorty of the system periodically returns to the initial one corresponding, in an untrapped case, to a homogeneous state.

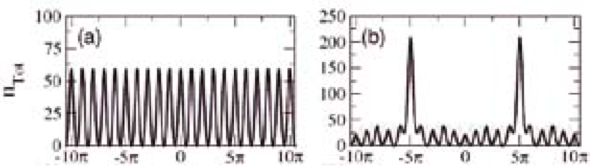

Figure 2: Total density of a polar (^{23}Na) spinor condensate prepared as a Bloch state at the edge of the first Brillouin zone of a 1D optical lattice of moderate depth (of 4 recoil energies) shown at (a) $t = 0$ and (b) after$t = 14$ ms of evolution at the band edge.

This general scenario persists in the presence of more complex spatial potentials, such as a periodic optical lattice. Our modeling of the nonlinear behaviour of spin-1 BECs with repulsive spin-independent interactions and either ferromagnetic or anti-ferromagnetic (polar) spin-dependent interactions, loaded into a 1D optical lattice potential [2] revealed that dynamical instabilities in both types of spinors leads to the formation of nonlinearly localized multi-component structures (as seen in Fig. 2), with the overall density displaying periodically recurring, irregular arrays of spatial solitons.

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Cascade atom in high-Q cavity: the spectrum for non-Markovian decay

B. J. Dalton[1] and B. M. Garraway[2]
[1] *ACQAO, Swinburne University of Technology, Australia*
[2] *Department of Physics and Astronomy, University of Sussex, UK*

The spontaneous emission spectrum for a three-level cascade configuration atom in a single mode high-Q cavity coupled to a zero temperature reservoir of continuum external modes is determined from the atom–cavity mode master equation using the quantum regression theorem [1]. Initially the atom is in its upper state and the cavity mode empty of photons. Following Glauber [2], the spectrum is defined via the response of a detector atom. Spectra are calculated for the detector located inside the cavity (case A), outside the cavity end mirror (case B - end emission), or placed to record emission sideways from the cavity (case C) (see Fig. 1). The spectra for case A and case B are found to be essentially the same. In all the cases the predicted lineshapes are free of instrumental effects and only due to cavity decay. Spectra are obtained for intermediate and strong coupling regime situations (where both atomic transitions are resonant with the cavity frequency), for cases of non-zero cavity detuning, and for cases where the two atomic transition frequencies differ. The spectral features for cases B(A) and C are qualitatively similar, with six spectral peaks for resonance cases and eight for detuned cases. These general features of the spectra can be understood via the dressed atom model [3]. However, case B and C spectra differ in detail, with the latter exhibiting a deep spectral hole at the cavity frequency due to quantum interference effects (see Fig. 2). The spectra are qualitatively different from the two-level atom case and are still to be confirmed in experiments.

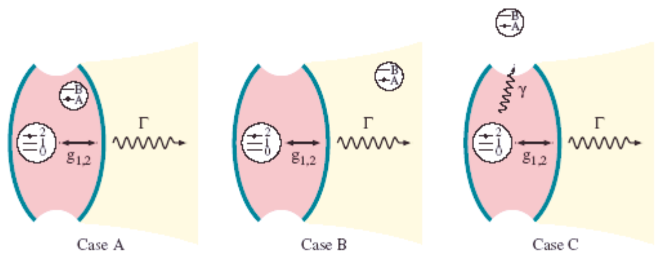

Figure 1: The cascade atom in a high-Q cavity with the detector atom in various locations. In case *A* the detector atom is inside the cavity, in case *B* it is outside the cavity output mirror and positioned to detect end emission and in case *C* it is outside the cavity positioned to detect side emission.

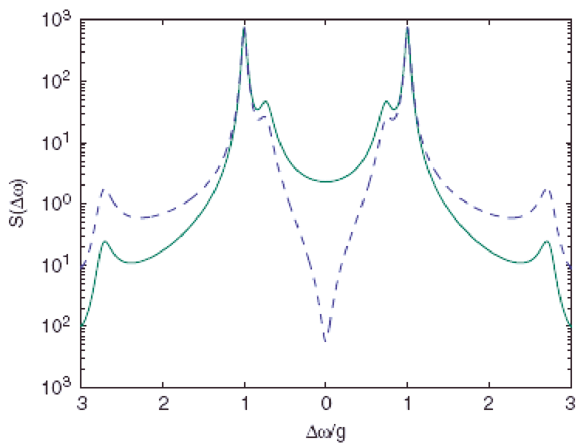

Figure 2: Cascade atom in high-Q cavity. SE spectra $S(\omega)$ versus spectral detuning from cavity frequency $\Delta\omega = (\omega - \omega_c)$. The case of resonance is shown, where each transition is resonant with the cavity frequency, $\delta = \bar{\delta} = 0$. The coupling constants are $g_1 = g_2 = 1$ and the detector coupling constants are $\mu = R_1 = R_2 = 1$. The cavity decay is $\Gamma = 0.1$. The solid line is for case $A(B)$-end emission and the dashed line is for case C-side emission.

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Permanent magnetic lattice on an atom chip

M. Singh, M. Volk, A. Akulshin, A. Sidorov, R. McLean and P. Hannaford
ACQAO, Swinburne University of Technology, Australia

Periodic optical lattices produced by the interference of intersecting laser beams are widely used for manipulating ultracold atoms and Bose-Einstein condensates and for performing fundamental physics experiments such as studies of low dimensional quantum gases and quantum tunnelling experiments including the superfluid to Mott insulator quantum phase transition. Periodic lattices also have potential application in quantum information since they may provide storage registers for qubits based on single atoms.

An alternative approach for producing periodic lattices for ultracold atoms is to use the magnetic potentials of periodic arrays of magnetic microtraps [1]. We have successfully loaded and trapped ultracold rubidium-87 atoms in a 1D permanent magnetic lattice of period 10 μm on an atom chip [2]. The periodic magnetic field potential is produced by a grooved silicon substrate coated with a multi-layer structure of perpendicularly magnetised TbGdFeCo of thickness 1 μm (Fig. 1). Ultracold rubidium atoms are evaporatively cooled in a Z-wire magnetic trap on the chip and then adiabatically transferred to the magnetic lattice potential by applying an appropriate bias field. Under our experimental conditions up to 2 x 10^6 rubidium atoms are trapped in about 150 lattice sites at less than 5 μm from the chip surface with a measured lifetime of about 450 ms at trap frequencies of up to 90 kHz.

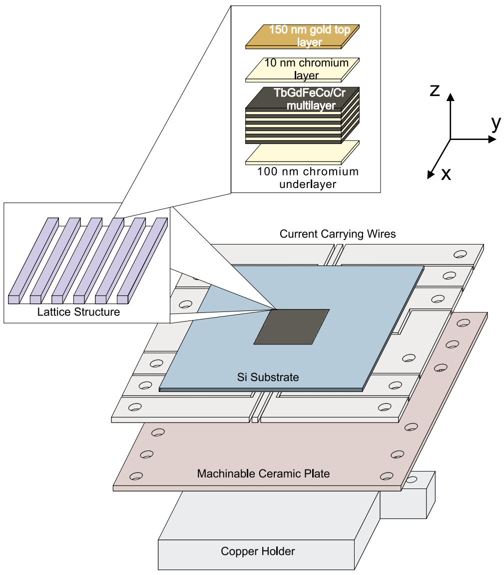

Figure 1: Periodic magnetic microstructure on an atom chip

Magnetic lattices based on permanent magnetic films are highly stable with low technical noise and low heating rates; they can have large and controllable barrier heights and large trap curvature leading to high trap frequencies; and they can be constructed with a wide range of periods, down to about 1 μm. The atoms need to be prepared in low magnetic field-seeking states, allowing RF evaporative cooling in situ and the use of RF spectroscopy. We consider magnetic lattices to be complementary to optical lattices, in much the same way as magnetic traps are complementary to optical dipole traps.

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Superfluid to Mott insulator quantum phase transition in permanent magnetic lattices

S. Ghanbari[1], P. Hannaford[1], J. F. Corney[2], P. B. Blakie[3] and T. D. Kieu[1]
[1]*ACQAO, Swinburne University of Technology, Australia*
[2]*ACQAO, School of Physical Sciences, University of Queensland, Australia*
[3]*Jack Dodd Centre for Photonics and Ultra-Cold Atoms, Department of Physics, University of Otago, New Zealand*

We study quantum degenerate Bose gases at finite temperatures in optical [1] and magnetic [2] lattices and in particular the superfluid to Mott insulator quantum phase transition. We investigate ultracold atoms in a grand canonical ensemble [3] and use the Bose-Hubbard model [4] which can describe the dynamics of ultracold atoms in periodic potentials such as optical and magnetic lattices. Based on a truncated number-state basis, in 1D, 2D and 3D, the Mott insulator lobes start melting at temperature $T_0 = 0.06\,U$, where U is the on-site interaction energy. Figure 1(a) shows the local compressibility

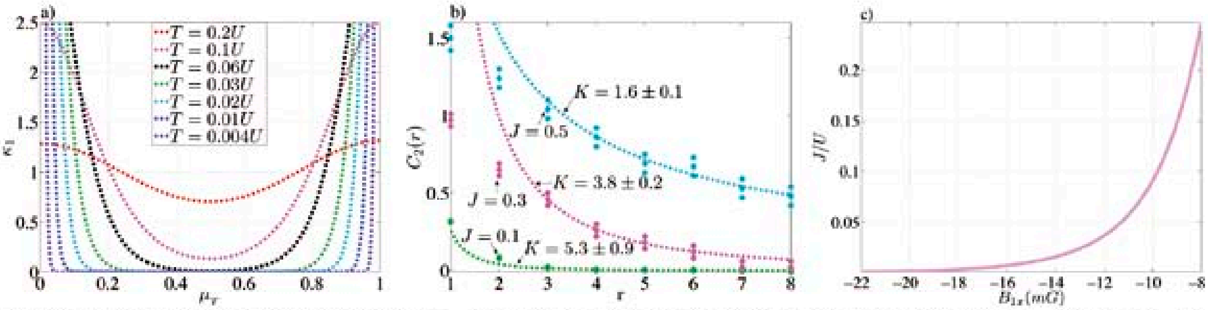

Figure 1: (a) The local compressibility κ_1, at each site, versus the target chemical potential, μ_T, for $J = 0$. (b) Atom-atom correlations, $C_2(r)$, as a function of r, the site number, for M=11, $\mu_T = 0.5$, $T = 0.5\,U$ and values of $J = 0.1, 0.3$ and 0.5. Diamonds and circles around them show the simulation results and their sampling error, respectively. Dashed lines are fits to the function $r^{-K/2}$, for $r \gg 1$, where K is the Luttinger parameter. (c) J/U versus B_{1x}, the x component of the bias magnetic field, in a 2D permanent magnetic lattice shown in figure 2 of reference [2], for $t_1/a = 0.3$, $t_2/a = 0.1$, $s/a = 0.5$ and $a = 1\ \mu m$ where t_1, t_2, s and a are geometrical parameters defined in [2] and a is the period of the lattice.

$\kappa_1 = \partial \langle \hat{n}_1 \rangle / \partial \mu_T$, at each lattice site, versus μ_T, where $\hat{n}_1$ and μ_T are the number operator at each lattice site and the target chemical potential at the temperature T, respectively, for $J = 0$ at different temperatures, and J is the hopping matrix element. At zero temperature, the Mott insulator phase is defined by $\kappa_1 = 0$. According to the gauge P representation, in a 1D system all the measures of the coherence between lattice sites and their relative values with respect to the average number of atoms in the central site increase when either the temperature is reduced or the hopping matrix element is increased. According to figure 1(b), at the constant temperature $T = 0.5\,U$, the atom-atom correlations $C_2(r)$, which are measures of the coherence between sites, increase with increasing J. Moreover, as J is increased the Luttinger parameter K decreases. Figure 1(c), based on the harmonic oscillator wave function approximation, shows that the critical value of the superfluid to Mott insulator quantum phase transition, $(J/U)_c = 0.043$ [5], is accessible in a 2D permanent magnetic lattice [2].

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Quantum tunneling in a nonlinear matter wave interferometer

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

Intrinsic interparticle interactions in atomic condensates lead to an interplay between dispersion and nonlinearity of matter waves, which supports a number of nontrivial collective excitations, including dark solitons in condensates with repulsive interactions. The recent experiments have demonstrated that such nonlinear excitations play an important role in atomic interferometers [1] based on BECs with repulsive atomic interactions, where they can be utilised to enhance the phase sensitivity of the devices. The construction of BEC interferometers involves time-dependent modifications of harmonic trapping potentials and the formation of dark solitons is associated with populating excited nonlinear eigenstates [2] of the confining trap.

The extensively explored mechanisms for population transfer between different eigenstates of a trapped BEC include non-adiabatic processes, Josephson tunneling, and Landau-Zener tunneling, which are also responsible for population transfer in linear systems. However, in a sharp contrast to linear systems, the quantum tunneling between different nonlinear eigenstates can be assisted by the nonlinear mean-field interaction even in the absence of crossing (and avoided crossing) of the energy levels. Up to now, this peculiar type of quantum tunneling remains poorly investigated.

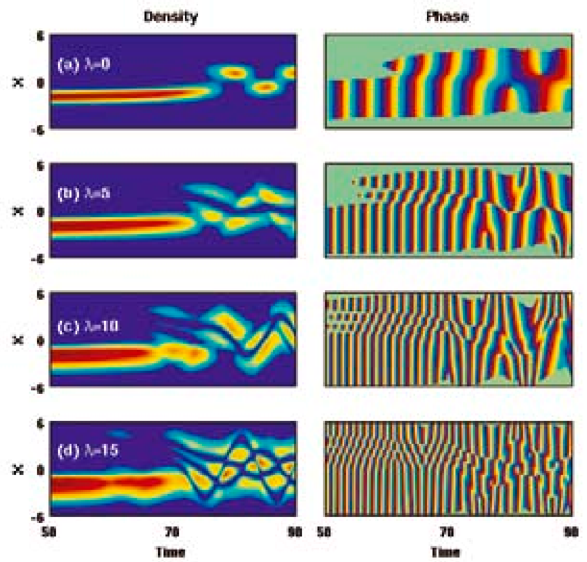

Figure 1: Evolution of the condensate density (left) and phase (right) for different values of the effective nonlinearity, showing that the number of dark solitons excited in the interferometer grows with increasing nonlinearity [3].

In this work we studied the intrinsic mechanism for the quantum tunneling assisted by repulsive mean-field interactions in a matter-wave interferometer [3]. We considered the dynamical recombination process of a BEC interferometer, in which a deep one-dimensional double-well potential is slowly transformed into a single-well harmonic trap. Our numerical simulations showed that multiple moving dark solitons are generated as a result of the nonlinearity-assisted quantum tunneling between the ground and excited nonlinear eigenstates of the system (see Fig. 1), and the qualitative mechanism is independent on the particular shape of the symmetric double-well potential. Furthermore, the number of the generated dark solitons is found to be highly sensitive to the strength of the effective nonlinearity. Finally, we demonstrated that the population transfer between different nonlinear eigenstates caused by the nonlinearity-assisted quantum tunneling can be quantified by a coupled-mode theory for multiple nonlinear eigenstates of the system.

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Theory of decoherence in Bose-Einstein condensate interferometry

B. J. Dalton
ACQAO, Swinburne University of Technology, Australia

A full treatment of decoherence, dephasing and trap fluctuation effects for double-well BEC interferometry using condensates with large boson numbers N has been developed [1]. This extends a simple theory of double-well BEC interferometry [2] based on a two mode approximation, which allows for possible fragmentations of the condensate into two modes [3] (these may be localized in each well), but is restricted to small condensates and only allows for transitions within the condensate modes and certain dephasing processes. The bosonic field operator is the sum of condensate and non-condensate mode contributions, the Hamiltonian being expanded in decreasing powers of $\sqrt{N}$, correct to the Bogoliubov approximation [4]. The density operator is mapped onto a phase space distribution functional, with the highly occupied condensate modes described via a generalized Wigner representation and the mainly unoccupied non-condensate modes described via a positive P representation. A similar hybrid approach has been applied to treat two coupled anharmonic oscillators [5]. An interferometry regime with macroscopic occupancy in only one condensate mode is assumed - the conditions to be found using the two-mode theory [2]. A functional Fokker-Planck equation (FFPE) for the distribution functional based on the truncated Wigner approximation is obtained, from which coupled Ito stochastic equations for condensate and non-condensate field functions are found. These equations contain deterministic and random noise terms - identifiable from the FFPE. Stochastic averages of the field functions give the quantum correlation functions that are used to describe interferometry experiments, and which exhibit decoherence and dephasing effects.

The Ito stochastic equations for the condensate field $\psi_C(\mathbf{s},t)$ are

$$
\begin{aligned}
& i\hbar\frac{\partial}{\partial t}\psi_C(\mathbf{s},t) = -\frac{\hbar^2}{2m}\nabla^2\psi_C + V\psi_C + \frac{g_N}{N}\{\psi_C^+\psi_C - |\phi_1|^2\}\psi_C \\
& +\frac{2g_N}{N}\{\psi_C^+\psi_C - \frac{1}{2}N\ |\phi_1|^2\}\psi_{NC} + \frac{g_N}{N}\{\psi_C\psi_C\}\psi_{NC}^+ \\
& +\frac{2g_N}{N}\{\psi_{NC}^+\psi_{NC}\}\psi_C + \frac{g_N}{N}\{\psi_{NC}\psi_{NC}\}\psi_C^+ \\
& +d_{C,C}\Gamma_C + d_{C,C+}\Gamma_{C+} + d_{C,NC}\Gamma_{NC} + d_{C,NC+}\Gamma_{NC+},
\end{aligned}
$$

the terms being displayed in decreasing powers of $\sqrt{N}$. In these equations V is the trap potential, the boson-boson interaction strength is g_N/N, the condensate wave function is $\phi_1(\mathbf{s},t)$ and satisfies a time-independent Gross-Pitaevskii equation. The $\Gamma_C, ..,\Gamma_{NC+}$ are stochastic noise fields, and the matrix elements $d_{C,C}, ..,d_{C,NC+}$ are related to the diffusion matrix in the functional Fokker-Planck equation. A similar equation applies for the non-condensate field $\psi_{NC}(\mathbf{s},t)$. The first line of the condensate equation is the time-dependent Gross-Pitaevskii equation, the mean field being depleted by one boson. The stochastic condensate and non-condensate fields are coupled together, each being affected by stochastic noise fields.

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** High impact article

PERSONNEL AND ASSETS

The most important asset for our research is creative people. The Centre was created by a dedicated group who now have excellent long-term opportunities for research through reduced teaching loads, improved laboratories and offices and the opportunity to travel with ACQAO and throughout the world. Several are fully funded by the Centre; others hold positions provided by the host universities.

During 2007 several staff members gained promotions in their universities. Chris Ticknor at SUT obtained an APD fellowship, Peter Drummond received a second ARC Professorial fellowship and Yuri Kivshar a second Federation Fellowship. Chris Vale joined the Centre as a Chief Investigator (CI) from the University of Queensland, and Brenton Hall, Nick Robins and Murray Olsen were promoted also to CI. The collaboration in the Centre has helped to focus the team on ambitious research projects.

The other big asset is our research laboratories. We have excellent research facilities at the ANU and SUT that are maintained at world class standard. Through funds from ACQAO and LIEF funding for 2006 and 2008, shared between ANU, SUT and UQ, and by focusing on a finite set of well defined goals, we can keep up with the technological developments in our research field and keep us competitive on a global stage.

Collaboration and Linkage

Through 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.

ACQAO Team in Hannover

Particularly strong links exist with the following international partners:

Laboraotoire Kastler Brossel in Paris with quantum imaging (C. Fabre, Hans-A. Bachor). Two joint PhD projects have been established (cotutelle) with students V. Delaubert completed in 2007; Julian Dugue with a third student, Jean Francois Morizur, starting in 2007)

IFRAF in Paris on atom optics experiments with Bosons and Fermions (K. Kheruntsyan, C. Savage, P. Drummond, J. Close, M. Davis, M. Leduc, G. Shlyapnikov, C. Westbrook, A. Aspect). In 2007 students from ACQAO visited the French laboratories and students from IFRAF visited the Australian laboratories.

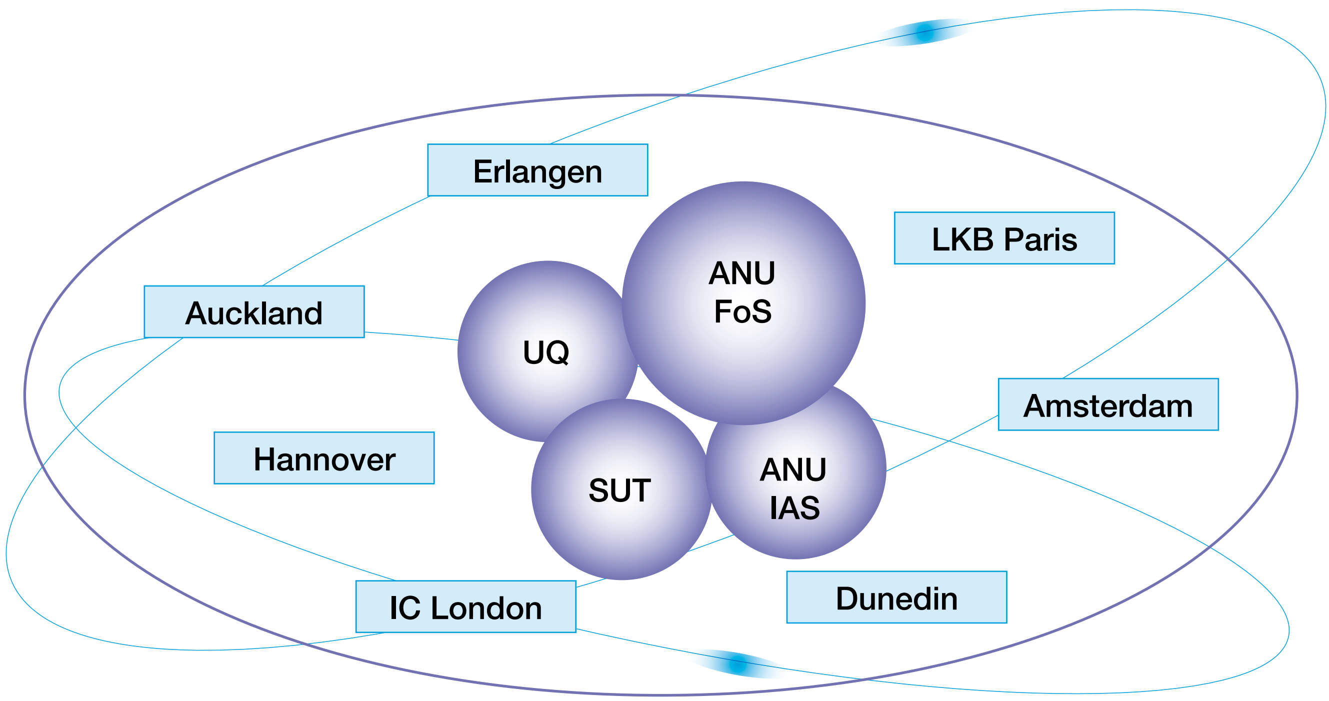
QUEST in Hannover on Feshbach resonances and developments of atom lasers (N. Robins, J. Close, J. Arlt, O. Topic) and the optimisation of squeezing (R. Schnabel, P.K. Lam).

Max Planck Institut Erlangen on the analysis of squeezing in optical fibres (J. Corney, P. Drummond, G. Leuchs) and optical entanglement (O. Gloeckl).

Danish Technical University with the development of spatial squeezing (M. Lassen, J. Janousek, P. Buchave, Hans-A. Bachor)

Otago University Dunedin where we have several joint projects (B. Blakie, S. Ghanbari, M. Davis, A. Bradley, W. Bowen, K. Longdell, G. Hetet, C. Gardiner, A. Wilson).

In May 2007 the UQ node hosted a workshop with 12 international visitors in Caloundra, which produced excellent discussions. We have a contract with IFRAF in Paris and the Sonderforshungsbereich SFB407 (now QUEST) in Hannover to organise annual quantum-atom workshops. In 2007 we held our fourth such workshop in Hannover with 24 participants from Europe and the fifth in Kioloa, Australia, with students from across Australia and New Zealand joining in. This has now created a unique international network for our students and helps them with their career as well as attracting young researchers to Australia.



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

ACQAO staff with international visitors in Caloundra, May 2007

In December 2007 we organised the first OSA conference on quantum-atom optics in Wollongong with 140 attendees. This meeting brought together many of the key contributors in this field and provided a valuable forum for discussions in this rapidly developing field. The conference also was an outstanding showcase for the research that Australia can deliver and the new ideas that we are creating.

ACQAO team at the 2007 QAO Conference in Wollongong

Commercialisation

While our research projects focus entirely on strategic fundamental goals, which are published in the open literature, we are using every opportunity to create additional intellectual property. Such IP will be shared between the inventors and the host universities as defined in our IP agreement. In particular the UQ and ANU theory groups are further developing the software code eXtensible multi dimensional Simulator (XmdS) http://www.xmds.org, which sees increasing use by groups around the world.

KEY PERFORMANCE INDICATORS (KPIs)

We believe that the performance of the Centre can be judged by both the quality and the quantity of our research outcomes and in particular the impact we have on the research community and the wider public.

We have a thriving theory core that produces results at an ever increasing pace. At the same time we have completed the building of all the initial experiments and achieved our first set of goals. All these outcomes are described in the Science section (pages 10–41) of this report.

We are publishing the findings in high impact journals where we achieve very good rates of citations. For 2007 we have exceeded the projected KPIs with 53 publications. Amongst these are 9 publications with particularly high impact factor in *Physical Review Letters* and *Nature Physics*.

We are now reaching a balance between recruiting new postgraduate students (8) and completions of postgraduate projects (6). The number of Honours students (8) is above our target. We are seeing longer and more intensive exchanges of students and staff internationally, with a strong interest from postgraduate students in Europe to study in our Centre and excellent offers of postdoctoral positions for our graduates.

Thanks to our international reputation and highly regarded workshops (Caloundra 2007) and conferences (Quantum Atom Optics down under, Wollongong 2007), we have exceeded our goals in regard to the number of visitors who came to Australia (36) to see our work and the number of invitations (23) we received to address international conferences.

We have formed an international student network with our partners in Paris and Hannover to organize international meetings and in 2007 we held two student workshops in Germany and in Australia (Kioloa 2007).

At the same time, we have maintained a widespread teaching program at all three Universities, with a total of 17 undergraduate and 2 professional courses in 2007. We have presented our ideas and goals to a wide section of the Australian Physics community. This includes the organisation of our science workshops and conferences and the establishment of a new outreach program “Physics for our Future” and several other outreach activities.

The creation of quantum technology is an expected long term outcome of our Centre’s work, and in the final years of our Centre we will accelerate our activities to work with potential end users towards the commercialization of our research. We already have created two patents and are developing our intellectual property.

In the table we show the KPIs for 2007 as well as the long term ratio between the KPI targets and accumulated achievements for the lifetime of the Centre 2003–07.

Key Performance Indicators (KPIs)

Key Result Area	Performance Measure	Target	Outcome 2007	Outcome Achievement ratio 2003–07
Research Findings	Quality of Publications International Ref. Journals with an impact factor > 5	4	9	1.60
	Number of publications/year	20	53	2.00
	Number of patents/year	0.3	0	2.00
	Invitations to address and participate in international Conferences/year	4	23	4.15
	Commentaries in professional journals National and international/year	3	6	1.00
Research Training and Professional Education	Number of postgraduates recruited/year	5	8	1.76
	Number of postgraduates completions/year	4	6	1.10
	Number of Honours students/year	5	8	1.28
	Number of Professional Courses to train non-Centre personnel/year	2	2	2.90
	Number and level of undergraduate and high school courses in the Priority area	7	17	2.43
International, National and Regional Links and Network	Number of international visitors/year	10	36	2.66
	Number of national workshops/year	1	1	1.40
	Number of international workshops/year	1	2	1.60
	Number of visits to overseas laboratories	18	123	3.44
	Contact with researchers related to the philosophical aspects of Quantum Physics	1	1	1.00
End-user Links	Number of commercialisation activities	2	0	0
	Number of government, industry and business briefings/year	2	4	1.40
	Number of Centre associates trained in technology transfer and commercialisation	2	1	0.70
	Number and nature of Public Awareness programs	4	13	1.95

OUTREACH/MEDIA/AWARDS

The year 2007 saw ACQAO personnel gain further recognition for their work with a number of awards granted. Other ACQAO staff members undertook to speak to school students, set up web pages or to organise workshops.

Media showed interest in quantum technology and in particular, Dr Ben Buchler talked with Radio ABC 666 about quantum superposition that was well received by the response of the listeners.

Dr Simon Haine relocated from the Australian National University ACQAO Node to work at the University of Queensland Node where he wrote a web page to focus on the work on teleportation that he and his fellow physicists had undertaken. Go to http://www.acqao.org/news/readMore_TeleportantionofMassiveParticles.html

Simon Haine (centre) with Joe Hope (left) and Nick Robins (right)

Dr Joel Corney from the UQ ACQAO Node co-ordinated workshops during January as part of the Siemen's Science Experience at his University. The workshop was called "Einstein, Quantum Physics and the Coolest Stuff in the Universe". The workshop was three days of hands-on science activities for Year 9 students that was held five times over two days, adding up to about a hundred students in total.

Dr Joe Hope, theorist at the ANU Faculty responded to the call from the Macqaurie Primary School in the Australian Capital Territory and became a "Scientist in Schools" persona. His web page has been very popular with the young students and ACQAO is encouraging other personnel to consider similar activities across the other Nodes. More on Dr Hope at http://starone.anu.edu.au/~joe/PetScientist/Pet%20Scientist.html

Joe Hope

Andy Ferris, a student at the UQ Node gave a presentation entitled "The History of Atoms" to two classes at Corinda State School during the month of October. His talk began with the basic idea of an atom presented by the Greeks, continued through to chemistry and the discovery of the atom to conclude with the current Bose-Einstein Condensates (BECs) that are so much a part of ACQAO's science.

June 6 at the Academy of Science in Canberra, Professor Hans-A. Bachor gave the first public lecture in the series, Physics For The Future. The title was "Photons — quantum ideas that could influence your life" and approximately 200 people filled the auditorium, including senior school children and their teachers. http://futurephysics.info/Future%20Physics/Lecture%20Archive.html

ACQAO Advisory Board Chair, Prof Alain Aspect, Director of Research CNRS, Institute d'Optique, Paris presented the third public lecture in the Physics for the Future series at the Australian Academy of Science in Canberra November 27 discussing the path From "Einstein's intuitions to quantum bits: a new quantum age ". This was popular with a large public attendance.

Ruth Wilson, Alain Aspect and Ken Baldwin at "Year of Physics" lecture

The ACQAO web site was developed further by introducing pod casts and lecture tapes as part of the public access to "What is Quantum-Atom-Optics"

An ACQAO paper on "Squeezing and Entangling a laser pointer" won the European Optical Society prize as the best publication in an EOS journal during 2006. Authors of the paper were Mikael Lassen, Vincent Delaubert, Charles Harb, Ping Koy Lam, Nicolas Treps and Hans-A. Bachor and the work was carried out in the ACQAO laboratories.

Some of the authors of the paper on "Squeezing and Entangling a laser pointer" L to R: Nicolas Treps, Hans-A. Bachor, Mikael Lassen and Vincent Delaubert

University of Queensland quantum physicist, Dr Matthew Davis won the UQ Foundation Excellence Award, receiving $60,000 to investigate Bose-Einstein condensates (BEC) to further understand the nature of the universe.

For scientific contributions to atom optics and laser spectroscopy, and for enhancing Australian optics nationally and internationally through professional scientific leadership, Dr Ken Baldwin, Deputy Director of ACQAO, was awarded the W. H. (Beattie) Steel Medal of the Australian Optical Society, the Society's highest academic award.

Prof. Peter Drummond was awarded the Moyal Medal and Lecturer for 2007 by Macquarie University for his distinguished contributions to physics.

Dr Margaret Reid

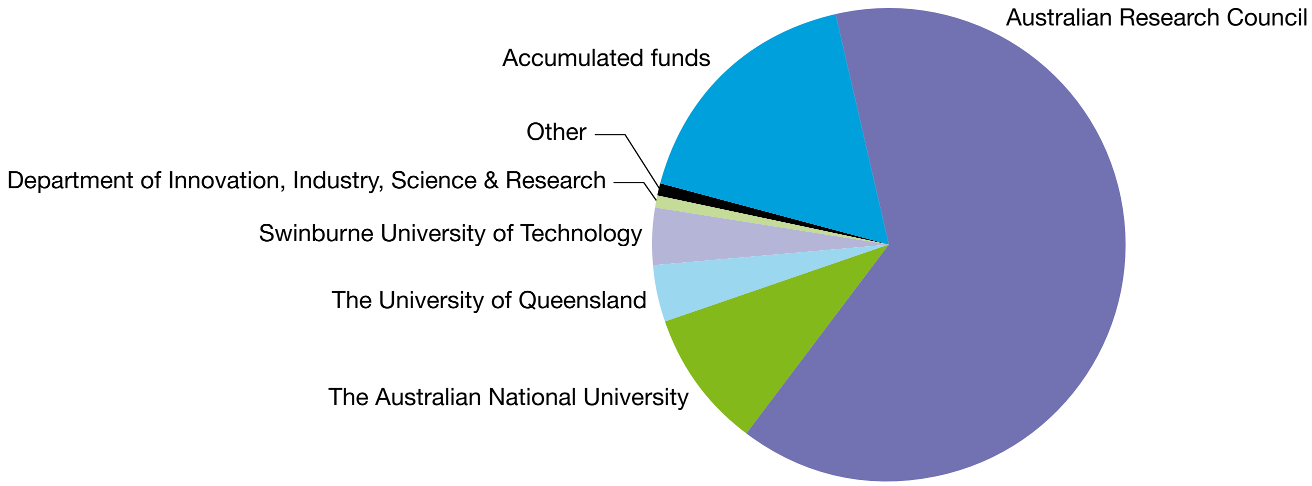
Dr Margaret Reid has been elected a Fellow of the Optical Society of America, the world's largest professional society for scientists working in optical and laser physics. Her nomination was for developing ways to test the fundamental concepts of nonlocality, squeezing, Einstein-Podolsky-Rosen paradoxes, entanglement and macroscopic superpositions in quantum optical systems'. Her studies in quantum squeezing and EPR entanglement led to the world's first experiment at Caltech, demonstrating EPR correlations in the form originally proposed by Einstein, Podolsky and Rosen — one of the most famous papers on the foundations of quantum physics.

Prof Yuri Kivshar

Prof Yuri Kivshar, ACQAO ANU Science Director, was presented with the ANU Peter Baume Award on December 21st. This is the university's most prestigious staff Award. Professor Kivshar's colleagues nominated him in recognition of his outstanding record of research achievement and his contributions to global Science and to the Australian National University.

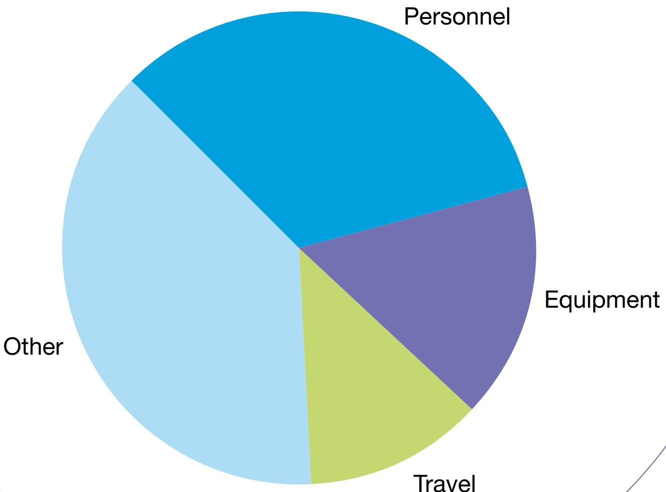
ACQAO INCOME 2007

Accumulated funds	$666,449.00
Australian Research Council	$2,435,266.00
The Australian National University	$356,000.00
The University of Queensland	$150,000.00
Swinburne University of Technology	$150,000.00
Department of Innovation, Industry, Science & Research	$32,500.00
Other	$26,338.00
TOTAL	**$3,816,553.00**



ACQAO EXPENDITURE 2007

Personnel	$965,383.00
Equipment	$465,191.00
Travel	$350,307.00
Other	$1,100,226.00
TOTAL	**$2,881,107.00**



ACQAO 2007 PERSONNEL

ANU FAC Node
Prof Hans-A. BACHOR
Dr John CLOSE
Prof Ping Koy LAM
Dr Craig SAVAGE
Dr Joe HOPE
Dr Nick ROBINS
Dr Ben BUCHLER
Dr Mattias JOHNSSON
Dr Christina FIGL
Dr Hongxin ZOU
Dr Max COLLA
Mr Guy MICKLETHWAIT
Mr Jiri JANOUSEK
Mr Neil HINCHEY
Mr Graham DENNIS
Mr Gabriel HETET
Mr Magnus HSU
Mr Matthew JEPPESEN
Mr Paul SUMMERS
Ms Katherine WAGNER
Mr John DEBS
Ms Rachel POLDY
Mr Daniel DOERING
Mr Julien DUGUE
Mr Paul ALTIN
Mr Jean-Francois MORIZUR
Ms Ruth WILSON

ANU IAS Node
Prof Ken BALDWIN
Prof Yuri KIVSHAR
Dr Andrew TRUSCOTT
Dr Elena OSTROVSKAYA
Dr Tristram ALEXANDER
Dr Chaohong LEE
Dr Robert DALL
Dr Michal MATUSZEWSKI
Dr Libin FU
Dr Denis SYCH
Ms Lesa BYRON
Mr Santiago CABALLERO BENITEZ
Mr Dario POLETTI
Mr Steve BATTISSON
Ms Deborah BORDEAU
Ms Wendy QUINN
Ms Kathleen HICKS

UQ Node
Prof Peter DRUMMOND
Dr Joel CORNEY
Dr Karen KHERUNTSYAN
Dr Matthew DAVIS
Dr John HEDDITCH
Dr Margaret REID
Dr Murray OLSEN
Dr Xia-Ji LIU
Dr Hui HU
Dr Ashton BRADLEY
Dr Simon HAINE
Dr Qiongyi HE
Mr Clinton ROY
Mr Paul SCHWENN
Mr Chris FOSTER
Mr Eric CAVALCANTI
Ms Sarah MIDGLEY
Mr Magnus OGREN
Mr Geoffree LEE
Mr David BARRY
Mr Andrew FERRIS
Mr Scott HOFFMANN
Mr Kalai Kumar RAJAGOPAL
Mr Andrew SYKES
Mr Tim VAUGHAN
Mr Sebastian WUESTER
Ms Beata DABROWSKA
Ms Stephanie GOLDING

SUT Node
Prof Peter HANNAFORD
Prof Andrei SIDOROV
Prof Russell MCLEAN
Dr Wayne ROWLANDS
A/Prof Bryan DALTON
Dr Brenton HALL
Dr Chris VALE
Dr Chris TICKNOR
Dr Grainne DUFFY
Dr Alexander AKULSHIN
Dr Michael VOLK
Dr James WANG
Mr Russell ANDERSON
Mr Paul DYKE
Mr Jurgen FUCHS
Mr Saeed GHANBARI
Mr Heath KITSON
Mr Mandip SINGH
Mr Gopisankararao VEERAVALLI
Mr Shannon WHITLOCK
Mr Holger WOLFF
Ms Eva KUHNLE
Mr Simon CUNNINGHAM
Mr Will BROWN
Ms Tatiana TCHERNOVA

Contact Us:

Australian Research Council Centre of Excellence for Quantum-Atom Optics

http://www.acqao.org

Professor Hans-A. Bachor, Research Director
ANU FAC Node + Main Office, Canberra
The Australian National University
Level 1 Physics Building 38A
Canberra, ACT 0200.
T: 61 2 6125 2811
F: 61 2 6125 0741
E: Hans.Bachor@anu.edu.au

Dr Ken Baldwin, Node Director
ANU IAS Node, Canberra
Research School of Physical Sciences & Engineering
The Australian National University
Canberra, ACT 0200.
T: 61 2 6125 4702
F: 61 2 6125 2452
E: Kenneth.Baldwin@anu.edu.au

Dr Joel Corney, Node Director
UQ Node, Brisbane
The University of Queensland
Physics Annexe Building 6
Brisbane, Qld 4072.
T: 61 7 3346 9398
F: 61 7 3365 1242
E: corney@physics.uq.edu.au

Professor Peter Hannaford, Node Director
SUT Node, Melbourne
Swinburne University of Technology
P O Box 218, Hawthorn, Vic 3122.
T: 61 3 9214 5164
F: 61 3 9214 5160
E: phannaford@swin.edu.au