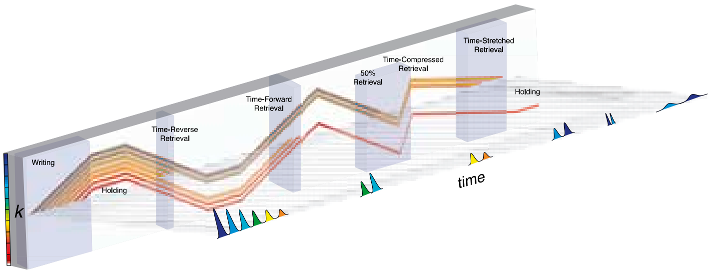

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report for the year 2009

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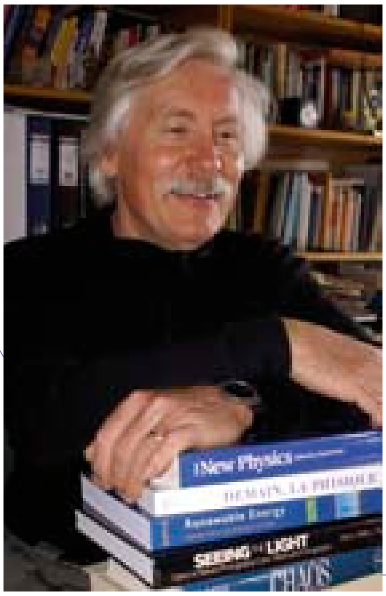
Foreword



Quantum-Atom Optics forms the foundation of future technologies. In a similar way that optics and electronics shaped the technologies we have today, we are convinced that quantum concepts will influence and improve communication, sensing, navigation and computing devices within a few decades. The evolution of this field involved basic theory and Gedanken experiments of the 1930s, first experimental demonstrations in the 1990s and refined systems and theory models in the present, leading to actual devices in 2020–2030.

This process of innovation will accelerate and ultimately create major new industries. This trend is being followed and supported in all leading industrial countries in the world, in particular USA, Europe, Japan and most recently China. In Australia the ARC Research Council Centre of Excellence for Quantum-Atom Optics (ACQAO) was selected as one of the few COEs funded in 2003. We started with a set of ambitious goals, both in theory and experiments, and succeeded in achieving each one of them. At the same time we have trained a group of outstanding young scientists who will take our science to the next level and across the world.

ACQAO has been one of the first to link the diverse techniques of optics, photons, ultracold atoms and coherent matter waves. Our strength is that we understand and can demonstrate the special quantum properties of large objects, involving thousands or even millions of atoms or photons, and observe the transition from the microscopic world of few particles to the macroscopic classical world. We start with systems dominated by quantum physics and investigate, step by step, the way quantum rules extend to practical systems.

ACQAO combines the skills and experience of many of the most productive Australian researchers in this field. We bring together experienced leaders in the field with successful younger researchers and with a highly talented and motivated group of graduate students. The Centre enjoys the support of the Australian National University (ANU) in Canberra, University of Queensland (UQ) in Brisbane and Swinburne Univerity of Technology (SUT) in Melbourne.

Reaching far beyond individual projects, ACQAO has built links across Australia and created a network with our international partners, in particular with key research Centres in Europe. We now have a whole range of scientific exchanges with staff and students working at different locations, linking ideas and expertise. Our model of long distance collaborations has been adopted in the formation of similar Excellence Clusters, for example in Germany and France. We have clearly demonstrated the effectiveness of the concept of ARC Centres of Excellence.

ACQAO links the theory of quantum statistics of Bosons and Fermions and nonlinear interaction with the operation of non-classical light sources and with Bose-Einstein Condensates (BECs) and atom lasers. Now in our eighth year of operation we reap the benefits from our long-term investment in people and laboratories. After achieving our initial goals and making them available to our peers, we are now fully involved in the second generation of projects which are aligned to, and in some cases even influence, the international agenda in quantum physics.

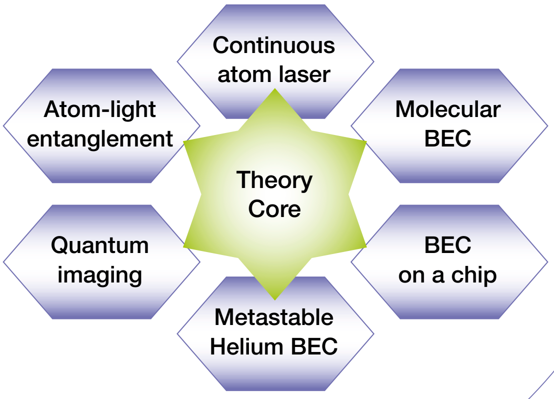
The highlights for 2009 reported here are numerous and include the optimization of atom lasers in both Rb and He*, quantum noise limited atom interferometry, unique studies of strongly interacting Fermi gases, demonstration of a quantum memory using photon echos in atoms, optical multimode entanglement of copropagating beams, universal laws for the statistical properties of Bosons and Fermions, the dynamics of ultra cold Bose gases and theory of vortex formation in BECs and the precision measurement of very long lived atomic states.

I hope this report stimulates your interest in our quest to create the foundations for future quantum technologies.

Hans-A. Bachor

Professor Hans-A. Bachor
Director

Quantum-Atom Optics — background and achievements



Our research goals

Optics and Photonics shape many aspects of our modern lives through the development of new technology. In recent years many devices are approaching a limit of performance given by the quantum uncertainty of light, introduced by the statistics of a stream of photons. Our fundamental research has developed methods that allow us to get around these quantum limits. By using squeezed light we can avoid the normal quantum noise limit and can improve the noise limitations of communication links and sensors. This can improve the signal to noise level of sensors and the channel capacity of communication lines, resulting in more efficient communication systems.

Already there are new applications being developed that exploit the concept of quantum encryption, which rely entirely on quantum ideas – in particular the concept of entanglement. This concept allows the sharing of information in separate systems well within the quantum uncertainty limits [p 32]. We have applied this concept not only to light [p 33] but also to atoms. One example is to reduce the uncertainty in the measurement of the phase of the atomic wave function to the quantum limit [p 23] and in the future, below this quantum limit [p 35].

The last few years have seen a rapid development of new tools in atom optics. We normally consider atoms as particles interacting via collisions in a gas or being close to each other in a liquid or solid. Today, 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. The quantum wave nature of atoms is used both to create new atomic systems and for practical applications.

Australia has established a strong international research profile in this field, both through pioneering theory work as well as state of the art experiments. In ACQAO we have built atom lasers that produce coherent matter waves. Soon we will 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, allowing for more detailed surveys of the Earth.

Both quantum and atom optics are based on the concept of Bosonic particles, photons and certain species of atoms – and the statistical properties of ensembles of Bosons determine and dominate the properties of devices such as lasers and atom lasers. The alternative concept is that of Fermions, which have very different statistical properties that apply to other atomic species. We have contributed to the rapid progress in both the experiments and theory of quantum degenerate Fermionic atomic systems. It is now possible to build molecular Bose-Einstein condensates (BEC) and to investigate the properties of dense Fermionic systems in the laboratory.

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 into different directions and which contain identical information, modulation and noise. Or they could be two, or more, beams of light, sets of particles, BECs, and atom laser beams that have identical properties.

Researchers in ACQAO have expanded the fundamental understanding of entanglement and its applications to practical systems [p 54, p 56]. The ACQAO ANU team has built optical sources that produce strong noise suppression, and entanglement. We have extended this work to very elegantly produce and detect entanglement between co-propagating laser modes [p 55].

Entanglement between individual atoms has been studied in detail. We are now looking to answer the question of how can we describe and generate entanglement between many particles. One of our teams at ANU has started investigating the properties of EPR entangled matter beams [p 54].

Creating and using Bose Einstein condensates

Groups of atoms can be manipulated, cooled, stopped and trapped until they reach such a low temperature that the atomic deBroglie waves overlap and quantum effects dominate. Theory has shown some years ago that the centre-of-mass wave function of atoms can be made to interfere. Bosonic atoms will make a rapid transition into a new state of matter once they cool below a critical temperature. The emergent BEC 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.

The SUT team has made clear observations of the spatial evolution of the condensate wave function within a two-component BEC [p 22]. At the same time, theory teams can model the dynamics and statistics of the BEC in great detail. In collaboration with external groups, the UQ team provided conclusive evidence for the formation of topological defects [p 30] and superfluidity in BECs [p 29]. Working with the University of Otago, they extended the usefulness of “classical field” methods for describing quantum and thermal dynamics and statistical mechanics of Bose gases [p 37].

Australia now has eight operational BEC experiments, five in Rubidium 87, and one each with Rubidium 85, metastable Helium 4, and Lithium 6. All are optimised for different studies and applications. Seven of these are part of ACQAO and are used to further refine existing technology, to make the apparatus simpler and more reliable for applications.

Atom lasers and interferometers

One more step leads from the BEC to the atom laser, a device that produces a coherent beam of atoms. The combination of atom lasers, optical beam splitters, and coherent wave-guides will become an important atom optic component, which can be found in devices used for applications such as atom holography and atom interferometry.

After our demonstration of the pumped atom laser in 2008, the ANU team compared different output couplers to increase the atom flux [p 36]. Simultaneously, a second ANU team showed the operation of an atom laser with metastable Helium 4. They were able to demonstrate single mode guiding of an atom laser beam, the equivalent of single mode optical fibre guiding for light, using an optical dipole potential as a waveguide. In this experiment, direct imaging of the transverse mode of guided matter waves was possible for the first time.

ACQAO now has two ultracold metastable Helium facilities, one of which was used to perform fundamental tests on atomic structure, to investigate the theory of Quantum Electrodynamics (QED). We carried out measurements of the complete ground state transition rates for the 2^3P Helium manifold [p 43].

From Bosons to Fermions

Recent years have seen a very rapid development of the theory concepts and complex experiments with fermions. In 2008 and 2009, a major highlight was in the theory of strongly interacting, ultra-cold fermions. This included a major breakthrough in exactly solving the one-dimensional polarized Fermi gas problem [p 26].

Fermionic atoms can combine into molecules, and can dissociate forming pairs of Fermions. In well-controlled situations this can lead to quantum correlations of individual atoms as well as creating many particle effects. Using our source of molecular BEC with Lithium 6 atom pairs, the SUT team has carried out a detailed investigation of the properties of two dimensional Lithium 6 Fermi gas using Bragg scattering [p 25].

Bridging quantum optics and atom optics

ACQAO combines, in a unique way, quantum optics and atom optics, through 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 atom laser beams. We are also 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. Our novel proposal of using the concept of photon echoes for storing and retrieving quantum information has been very successful in delaying and storing and reordering information with high efficiency [p 18].

The ANU team has been able to test the feasibility of quantum information storage by transmitting squeezed light without additional noise through atomic samples that show electro-magnetically induced transparency (EIT). At the same time the SUT team propose alternative forms of quantum memories that are worth exploring [p 19].

Leading the way to the future

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

Outstanding examples can be seen in our work on macroscopic self-trapping of ultracold Bose-Fermi mixtures [p 28] and spontaneous four Wave mixing of the matter waves, which was observed by our collaborators in France [p 31].

ACQAO aims to provide the scientific tools required to develop quantum and atom optics into a whole new field of quantum technology. Some examples, such as the operation of quantum communication and Cryptography are already making rapid progress and are performed at the ANU outside the Centre, and in other laboratories in Australia and around the world. As a Centre of Excellence our goal is to create new ideas, experimental demonstrations and simulations. Our work over the next eight years will pave the way for applied work in quantum technology within 10–15 years.

Research Highlights

Project – Atom laser

Dr Nick Robins

Dr Nick Robins completed his PhD at the ANU and has been part of ACQAO since inception. He was awarded an ARC APD in 2004, and became an ARC QEII fellow in 2010. Dr Nick Robins leads the atom laser program together with Prof. John Close. They also jointly coordinate the honours program and currently supervise 5 PhD and 2 honours students.

Using atoms instead of light is one of the pathways to higher sensitivity in many interferometric measurements. Within the atom laser program, we study and improve coherent atom beams with a view of applying them to precision measurements. Our atom laser is extracted from an ^{87}Rb Bose-Einstein Condensate (BEC), an ultracold sample of about one million atoms.

Since 2003, we have studied the properties and limitations of atom lasers produced with different output couplers and different internal states, looking at noise and flux limitations, linewidth, and at spatial properties [1–5]. In this context, we produced the first quasi-continuous Raman atom laser. This is a major advance, since they have inherently less classical noise, a higher maximum flux, and a beam profile that is closer to the quantum limit than the more commonly used rf-outcoupled atom laser.

We have produced the world's first pumped atom laser [6], which is one of the milestones towards a truly continuous atom laser. Recently, we have demonstrated a shot noise limited atom laser interferometer [7]. In addition, we have started to explore the possibility of changing the strength of atomic interactions by manipulating the scattering length through a Feshbach resonance [page 45].

[1] N.P. Robins, *et al.*, Phys. Rev. A 72, 031606 (2005).

[2] N.P. Robins, *et al.*, Phys. Rev. Lett. 96, 140403 (2006).

[3] J. Dugue, *et al.*, Phys. Rev. A 75, 053602 (2007).

[4] M. Jeppesen, *et al.*, Phys. Rev. A 77, 063618 (2008).

[5] J.E. Debs, *et al.*, Optics Express 17, 2319–2325 (2009).

[6] N.P. Robins, *et al.* Nature Physics 4, 731 (2008).

[7] D. Döring, *et al.*, Optics Express 17, 20661 (2009).

Project – Strongly interacting Fermi superfluids

Dr Chris Vale

Dr Chris Vale joined the cold molecules group at SUT at the beginning of 2007, shortly before the group produced their first molecular BECs. Since 2008, Chris has been project leader of the molecular BEC program in ACQAO. He played a key role in establishing the technique of Bragg spectroscopy in the laboratory and demonstrating its broad applications.

Researchers in the molecular Bose-Einstein condensate laboratory of ACQAO at SUT have recently made an important breakthrough in understanding the behaviour of strongly interacting Fermi superfluids. Using Bragg spectroscopy and a new analysis technique based on the f-sum rule, they have demonstrated a previously unknown universal property of strongly interacting fermionic superfluids. Pairing, the precursor to all fermionic superfluids, is shown to follow a simple universal power law dependence on the momentum. This result applies not only to fermionic gases in the crossover from Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS), but to all fermioinic systems in which the characteristic length scale of interparticle interactions is larger than the mean particle separation.

In 2003, the SUT team embarked on an ambitious program to produce a BEC of molecules. Previous experiments around the world had only ever condensed atoms; while molecules are far trickier due to their complex internal structure containing many rotational and vibrational levels. However, in 2003 it was shown that bosonic molecules comprised of two fermionic atoms, could be created through association near a Feshbach resonance. These molecules were surprisingly long lived and the first molecular condensates were created in the same year in Austria and the USA. It was soon realised that Fermi gases near Feshbach resonances provide a model realisation of the BEC-BCS crossover, a topic which has received much attention in condensed matter physics due to its possible connections with high temperature superconductivity.

The SUT team decided to pursue molecular BEC with ^{6}Li atoms and developed all the experimental apparatus necessary to cool Li atoms in an optical trap. In addition to the regular lasers and ultrahigh vacuum systems, the need to generate the required stable and large (kiloGauss) magnetic fields places stringent requirements on the setup. In 2007, the group produced its first molecular BECs [1].

In 2008, the group performed experiments using Bragg spectroscopy to study pairing through the BEC-BCS crossover [2]. These results have been widely cited, as it had not previously been realised that Bragg experiments with strongly interacting Fermi gases could yield such quantitative results. The theory team, since 2008 at SUT, derived a new universal short-range property of fermionic pairs. They proposed a way to experimentally verify this prediction using Bragg spectroscopy that lead to demonstrating the universal behaviour of pairing late in 2009, which has now been submitted for publication in Nature Physics [3].

[1] J. Fuchs *et al.*, J. Phys. B 40, 4109 (2007).

[2] G. Veeravalli *et al.*, Phys. Rev. Lett 101, 250403 (2008).

[3] H. Hu *et al.*, submitted, Nature Phys. (2010), arXiv:1001.3200 (cond-mat.quant.gas).

Project – Theory of ultracold atomic Fermi gases

Dr Hui Hu

Dr Hu joined ACQAO as a visiting researcher in 2005. With Prof. Peter D. Drummond and Dr Xia-Ji Liu, he has contributed many original ideas to develop novel theories for strongly interacting quantum gases. In 2009, he was awarded an ARC QEII Fellow.

The Fermi theory project has been able to understand, predict and unravel the quantum states of matter in ultracold atomic Fermi gases, subject to the critical tests of current experiments at temperatures down to a nano Kelvin (10^{-9} K) above absolute zero. This achievement is based on new theoretical methods we developed to describe the strongly interacting many-body systems.

Manipulation of atomic Fermi gases is a core project of ACQAO. Our main motivation was to provide parallel theoretical support, by developing novel analytical and computational tools. This is a challenge due to the strongly correlated nature of underlying systems. In close interaction with the teams at Duke (John Thomas) and Rice University (Randy Hulet), we developed several powerful tools, including a strong-coupling diagrammatic theory to unravel the universal thermodynamics [1] and the use of exactly solvable models to predict an exotic superfluid phase [2]. At this stage, in collaboration with theoretical teams at Toronto (Allan Griffin) and BEC Center Trento (Sandro Stringari and Lev Pitaevskii) and the experimental team at SUT (Chris Vale), we address issues that are crucial to understand and engineer the superfluidity in the strongly interacting regime.

In 2008, we focused on the development of a controllable quantum cluster expansion theory and demonstrated its wide applicability in a trapped, strongly interacting quantum gas [3]. Our theoretical prediction of expansion coefficients was confirmed by Salomon's group at ENS Paris. In 2009, we extended the technique to dynamic properties and solved completely the high-temperature problem in the strongly interacting limit. We also predicted new Fermi universality law on the structure factor, which was confirmed recently at SUT.

Our ultimate aim is to bring fundamental knowledge to quantum many-body systems, based on the platform of clean and experimentally controllable ultracold atomic Fermi gases.

[1] H. Hu, *et al.*, Nature Phys. 3, 469 (2007).

[2] H. Hu, *et al.*, Phys. Rev. Lett. 98, 070403 (2007).

[3] X.-J. Liu, *et al.*, Phys. Rev. Lett. 102, 160401 (2009).

Project – Quantum Imaging

Dr Jiri Janousek

Dr Jiri Janousek has been involved in the quantum imaging project since 2006, first as a visiting PhD student and now as postdoctoral research fellow. His role is to drive forward the development of novel squeezing, entanglement and detection techniques in the spatial domain. He is particularly interested in the challenge to build a device that generates squeezing in many spatial modes simultaneously.

The quantum imaging project has been able to demonstrate the principle of new communication technology by extending the concept of entanglement to spatial modes co-propagating within one beam of light. This is the culmination of a series of experiments that developed the techniques for generating light in spatial modes, extended our understanding of quantifying entanglement and allowed us to systematically optimise our apparatus.

At the start of ACQAO the main motivation was to understand the quantum nature of images and, at the same time, to develop the instruments to carry out spatial measurements with a precision better than the quantum noise limit [1]. In close collaboration with the team at LKB Paris (Nicolas Treps, Claude Fabre and two Cotutelle students), we developed the concept of multimode quantum optics and realised that, using our spatial modes, we had the ideal tools at ANU to address questions that are important to quantum communication. At the same time the LKB team started with a parallel realisation, using laser pulses and temporal modes.

In 2008, we focused on spatial entanglement and experimentally demonstrated both inseparability and EPR for the position and momentum of two laser beams [2]. In 2009, we showed that we could produce entanglement with two co-propagating spatial modes using an elegant and simple apparatus [3]. Now we are able to generate and control the process of entanglement using spatial light modulators, and can show that the mode of the squeezed light can be transformed efficiently and with sufficiently low loss.

The aim is to build a simple, elegant apparatus that can generate, propagate, control and detect a beam with multiple modes, which carry quantum information in the form of cluster states or other higher order forms of entanglement.

[1] Nicolas Treps, *et al.*, Science 301, 940 (2003)

[2] K. Wagner, *et al.*, Science 321, 541 (2008)

[3] J. Janousek, *et al.*, Nature Photonics 3, No 7, 399 (2009).

Project – Atom-Light Entanglement

Dr Ben Buchler

Dr Ben Buchler completed his PhD at the ANU in 2002 and was involved in developing the ALE program with ACQAO from the very start. After some time working as a post-doctoral fellow at ETH Zurich, he returned to lead the ALE program in 2006. He is involved in teaching at the undergraduate level and supervises a number of PhD candidates.

The atom-light entanglement program has developed a new form of coherent optical memory. The gradient echo memory (GEM) is a photon echo technique first proposed by ACQAO student Gabriel Hétet and demonstrated in an ensemble of two-level atoms in collaboration with the group of Matthew Sellars [1]. Most recently we have shown how this system can be used to realise a random access coherent optical memory [2].

The overall aim of the atom-light entanglement program is to deliver convergence between quantum and atom optics, fulfilling a key goal within ACQAO. The main area of investigation has been looking for methods to map quantum states of light, in particular squeezed states, onto atomic ensembles and back to photonic states. This kind of controllable atomic memory for quantum states of light has important applications within many quantum information systems.

The project started by developing squeezed sources of light at frequencies compatible with rubidium. Our PPKTP squeezed source [3] held, at one point, the record for squeezed light generation at 795nm with over 5dB of measured quantum noise suppression. Attention then turned to measurements of quantum state transfer through a window of electromagnetically induced transparency (EIT) in rubidium vapour. Under some conditions, EIT was shown to perform poorly [4], although with some patience, substantial delay of squeezing was achieved along with the first demonstration of transmission of biased entanglement through EIT [5].

In 2008 and 2009, full attention was turned to the GEM system. After the initial demonstration in two-level atoms [1], we showed how the memory can be extended to three-level atomic systems [6] and also showed that the memory can be described as a normal mode system in Fourier space [7]. It was this picture that provided the insight required to design the random access system [2].

[1] G Hetet, *et al.*, Phys. Rev. Lett. (2008) vol. 100 (2) 023601

[2] M. Hosseini, *et al.*, Nature vol. 461(7261) pp. 241–245 (2009)

[3] G. Hétet, *et al.*, Journal of Physics B, 40(1), 221, (2007).

[4] M.T.L. Hsu, *et al.*, Physical Review Letters, 97, 183601, (2006).

[5] G Hétet, *et al.*, Opt Express vol. 16 (10) pp. 7369 (2008)

[6] G Hétet, *et al.*, Optics Letters vol. 33 (20) pp. 2323 (2008)

[7] G Hétet, *et al.*, Phys. Rev. Lett. vol.101, 203601 (2008)

Project – Atom-atom correlations and thermodynamics of one-dimensional Bose gases

Dr Karen Kheruntsyan

Karen Kheruntsyan is a CI and a founding member of ACQAO. He was awarded an ARC CoE Fellowship in 2005 for his contributions. He served in the role of the Deputy Director of the UQ Node in 2004–2006. ACQAO has enabled UQ to build an exceptional group of mid-career researchers in the theory of ultra-cold atomic gases, which has now established itself as a significant player internationally.

Karen Kheruntsyan is a project coordinator in ACQAO and leads the theoretical programs on 1D Bose gases and molecular Bose-Einstein condensates. He has initiated a number of international collaborations, including with some of the most renowned research teams in France, USA, Netherlans and UK.

The one-dimensional (1D) Bose gas with repulsive contact interactions is one of the simplest paradigms we have of a strongly correlated quantum system. This is because the underlying theoretical model is among the handful of very unique, exactly integrable models in quantum many-body theory. Hence, the understanding of this system carries significant general interest in quantum many-body physics. Lieb and Liniger first solved the model in 1963, with a subsequent important contribution coming from the Nobel Laureate C.N. Yang and his brother C.P. Yang who in 1969 solved for the finite-temperature thermodynamics of the system. For more than 40 years these exact solutions remained a tour-de-force of mathematical physics, until the model was realised in 2001 in ultra-cold atomic gases trapped in highly anisotropic, cigar shaped traps.

The experiments on 1D Bose gases posed important questions, such as what are the different physical regimes of the system and how does one probe these regimes? In 2003, Dr Karen Kheruntsyan of UQ, together with Prof. P.D. Drummond of SUT and their international colleagues Prof. G. Shlyapnikov of the Université de Paris XI and Dr D. Gangardt of the University of Birmingham, published an inspirational paper on atom-atom pair correlations in a 1D Bose gas [1]. By calculating the atom-atom correlations at arbitrary interaction strengths and temperatures, the team was able for the first time to map out the complete phase diagram of the system and propose simple correlation measurements that could test the theoretical predictions experimentally.

In 2004, just 9 months after the publication of the original paper, the theoretical predictions of Kheruntsyan and the team have been tested and confirmed experimentally in the Nobel Prize winning research laboratory of Professor Phillips at the US National Institute of Standards and Technology [2].

Furthermore, in 2008 Kheruntsyan teamed up with the experimental group of N.J. van Druten of the University of Amsterdam and published a well cited paper on the thermodynamic properties of a 1D Bose gas created on an atom chip [3]. The team has succeeded in comparing the temperature and the atom number density of a 1D quantum gas to the Yang-Yang thermodynamics theory. This publication was selected by the PRL editors as an “Editors’ Suggestion” to promote reading across fields.

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[2] B.L. Tolra, *et al.*, Phys. Rev. Lett. 92, 190401 (2004).

[3] A.H. van Amerongen, *et al.*, Phys. Rev. Lett. 100, 090402 (2008).

Project – BEC on Atom Chip

Associate Professor Andrei Sidorov

Associate Professor Andrei Sidorov is a CI and a founding member of ACQAO. He is leading the Atom Chip project and the Atom Optics program at SUT.

At the start of ACQAO we aimed at studying decoherence effects and exploring the feasibility of on-chip BEC-based sensors. In 2005, we produced our first BEC in a magnetic film microtrap on an atom chip and carefully characterized random magnetic fields and the cloud fragmentation. Our first on-chip sensor of magnetic field gradients [1] demonstrated that adiabatic splitting of a BEC and the precision measurement of atom number in two modes can be used for precision sensing of asymmetric potentials including gravity. We also demonstrated the trapping of cold atoms in multiple sites of a 10 mm period magnetic lattice.

In 2008, we observed a spectacular evolution of the relative phase in a two-component BEC where the conventional time dependence of the phase is accompanied by spatial dephasing of the condensate and a relatively fast decay of the interference fringes [2] and [page 22]. These observations are crucially important for precision measurements of a condensate phase and future applications of BEC interferometers and on-chip atomic clocks. In 2009, we observed self-rephasing of the condensate, spin-echo enhancement of the interference contrast and extended coherence times.

In the next few years we will focus on absolute and relative atom number fluctuations in two modes of a binary BEC interferometer and the generation of spin-squeezed multi-particle quantum states. The ultimate goal will be to improve the precision of interferometric measurements beyond the standard quantum limit. This task is closely associated with the production of entangled multi-particle quantum states.

From a personal perspective it has been fascinating to realise the setting up of challenging tasks, the emergence of unexpected solutions, an influx of talented young researchers attracted by the opportunity to do cutting-edge research, and the incredible growth of quantum-atom optics in Australia. Our notable highlights include the first BEC, the on-chip sensor of magnetic fields, and the development of a theoretical model of random magnetic fields, which explicitly explains the observed results.

[1] B.V. Hall, *et al.*, Phys. Rev. Lett. 98, 030402 (2007)

[2] R.P. Anderson, *et al.*, Phys. Rev. A 80, 023603 (2009)

Project – Experiments with Ultracold and Degenerate Metastable Helium Atoms

Dr Andrew Truscott

Dr Andrew Truscott is a founding member of ACQAO and has headed the He* BEC group from its inception. Arriving from Rice University in late 2001, where he worked as a postdoc in Prof. Randy Hulets group, he is now a Fellow at the Research School of Physics and Engineering.

The He* BEC project was started as a result of the formation of ACQAO. It is one of the few experimental projects that had to start from a bare laboratory; indeed the actual laboratory refurbishment itself was a joint ACQAO-ANU initiative. From those early beginnings in 2003, the project has evolved to a program involving five staff, four PhD students and numerous honours students. We now have two fully operational experimental rigs, with one concentrating on atomic physics experiments, while the other is the original purpose built BEC machine.

We achieved our first metastable helium (He*) BEC in late 2006, three years after the formation of ACQAO. At the time this was only the fourth demonstration of an excited state condensate. Since our original demonstration we have used the unique detection capabilities of He* to probe the physics involved in the formation of an atom laser. In particular, our group has observed quantum mechanical interference fringes on the output profile of the atom laser [1], as predicted by Mϕlmer. Demonstrated locking of the atom laser beam [2], by using the ions produced in the He* atom laser formation as a feedback signal. Produced paired atom laser beams [3], as a direct result of four wave mixing, that may be entangled and used an optical potential to guide an atom laser beam [4], analogous to an optical fibre.

Besides our atom laser studies, we have also performed a number of interesting atomic physics experiments. Including measuring accurately, for the first time, the lifetime of the metastable state of He* [5]. Moreover, we have begun the first experiments of a mixed alkali (Rb) – excited state (He*) cold atom mixture. Many scientists thought such a mixture would be unstable due to the high internal energy of He*, however our initial results suggest such a novel mixture may well be stable [6].

In the coming years we plan to embark on a number of experiments that will test the foundations of quantum mechanics. In particular we want to carry out experiments to test the famous Einstein-Poldosky-Rosen paradox.

[1] R.G. Dall, *et al.*, Optics Express, 15, 17673 (2007).

[2] R.G. Dall, *et al.*, Optics Express, 16, 14716 (2008).

[3] R.G. Dall, *et al.*, Physical Review A 79, 011601R (2009) (Rapid Commun.)

[4] R.G. Dall, *et al.*, Physical Review A 81, 011602R (2010) (Rapid Commun.)

[5] S.S. Hodgman, *et al.*, Physical Review Letters, 103, 053002 (2009).

[6] L.J. Byron, *et al.*, New Journal of Physics 12, 013004 (2010).

Project – Matter waves in optical lattices and atomic waveguides

Dr Elena Ostrovskaya

Dr Ostrovskaya is a CI and a founding member of ACQAO, currently leading the ACQAO theory node at the Nonlinear Physics Centre, Institute of Advanced Studies, ANU. Her work was supported by an ARC APD fellowship in 2003–2005 and ARC ARF fellowship in 2007–2011.

A BEC loaded into an optical lattice is one of the most flexible, "clean", dynamically reconfigurable systems available to physicists. Matter-wave nonlinearity due to the atomic interactions and tunability of the lattice potential make this system analogous to nonlinear photonic bandgap structures for coherent light [1]. This theory project was established with the aim to understand the nontrivial nonlinear dynamics of BECs in a lattice and suggest methods for efficient control and manipulation of the matter wavepackets, in a manner similar to manipulation of light waves in periodic photonic structures.

At the start of the ACQAO we have pioneered the research on the interplay between the effects of lattice periodicity and matter-wave nonlinearity, which can lead to localization of the condensate in the form of atomic gap solitons, vortices and other complex topological structures (see Ref. [2] and references therein). We then investigated quantum noise properties of localized states, dynamics of spinors and Bose-Fermi mixtures, and the possibilities for quantum information processing with optical lattices [3].

Recently, our activities are focusing on the controlled manipulation and transport of matter waves both in optical lattices and ultracold atom-guiding structures created by optical and magnetic traps. In particular, we have investigated driven periodic potentials and demonstrated mass-dependent transport of BEC in an optical ratchet potential [4] and dynamical routing of BEC wavepackets through an optical lattice [5]. Our overarching goal is feasibility studies for future applications of ultracold atoms in atomic interferometry and quantum information processing.

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Project – Atom laser theory

Joe Hope

Joe Hope is a founding CI of ACQAO, with a strong interest in atom lasers and their limits and possibilities. Atom lasers have been a constant theme of his work in the Centre, but he has also been involved in a wide range of activities and collaborations. In 2006, he began building a group focussing on quantum control in parallel with ACQAO. He is currently excited by a range of new possibilities for making revolutionary new theoretical tools that allow easier quantum field theoretical simulations of degenerate ultra-cold gases with high nonlinearities. These new tools may also allow efficient simulation of certain condensed matter systems.

In 2009, the atom laser theory group at the ANU examined the processes underlying the quasi-continuous pumping of an atom laser, characterised the possibilities for using thermal sources for continuous atom laser production, described the generation of correlated atom laser beams via four-wave mixing [1], proposed methods of generating squeezed atom lasers from outcoupling [2], described a filter for a BEC undergoing phase-contrast imaging [3], and developed methods for modelling conditional quantum systems [4].

The group has published with all three ANU-based experimental projects within ACQAO, has examined a range of theoretical topics and developed new theoretical and computational techniques and tools. From before the start of ACQAO, the theory group was involved with developing and understanding the properties of atom lasers, and this remained a constant theme throughout the Centre. Over this time, we examined the mode selectivity properties of pumped atom lasers, the behaviour of BEC and atom lasers undergoing feedback, and the practical limitations in flux and transverse mode properties of outcoupled atom lasers in a range of configurations with different outcoupling mechanisms and relevant internal mode structures. We also examined minimally destructive optical detection of atoms, culminating in a general theorem that demonstrated that no multi-photon optical method of detecting atoms could produce a superior measurement compared with existing schemes. We also took the main role in investigating possibilities for the later starting atom-light entanglement project. This resulted in theoretical examinations of existing quantum memory schemes, and theoretical tools that helped the ALE group after they were sufficiently established to take over this work. In collaboration with the UQ theory node, the group also developed a range of schemes for coupling the quantum state of light and a BEC, allowing for an effective optical memory, entanglement between laser and atom laser beams, production of squeezed atom lasers.

The group is currently focussing on continuing to refine schemes for controlling atom lasers, with the goal of proposing a measurement-based feedback experiment for the atom laser experiment. We are also working to produce new theoretical methods for the simulation of nonlinear quantum systems.

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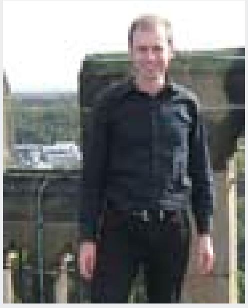
Project – Fermions Simulations



Joel Corney (Chief Investigator)

Dr Joel Corney became a founding CI of ACQAO after returning from postdoctoral work at the Technical University of Denmark. He is now a senior lecturer at UQ, where his main research interests are fermion simulations, quantum squeezing and novel stochastic methods for quantum fields.

The first-principles simulations of the dynamics of a Bose-Fermi system outlined in the science report [page 28], builds upon the foundations laid by the ACQAO fermion simulation project.

How can a system of many interacting particles be efficiently simulated on a computer? How do you deal with the incredible complexity of quantum mechanics, where a complete description entails keeping track of every possible configuration of particles? It was questions such as these that led us to formulate new ways to represent quantum states. We were searching for a probabilistic, overcomplete and yet efficient representation that suited the physics of ultracold atoms.

A representation based on Gaussian operators provided an elegant formalism that matched these criteria [1]. Importantly, it was able to represent fermionic states. While experiments in ultracold fermions were moving to the vanguard of matterwave research, there was not yet available the range of theoretical techniques that there were for bosons.

We first applied the approach to the Hubbard model [2], which is speculated to account for the kind of high-temperature superconductivity observed in 2D condensed matter systems. The method was taken up and extended by computational physicists in ETH Zurich, Würzburg, Aachen and Tokyo [3].

More recently, we have focused on using the Gaussian technique to focus on real-time dynamics [4]. As detailed elsewhere [page 42], we simulated the dissociation of a Bose-Einstein condensate of molecules into pairs of fermionic atoms. Phase-space methods for bosons have been around for some time, but this is the first time that a phase-space method for fermion dynamics has been demonstrated for a large interacting system.

A major focus of the proposed future ACQAO is quantum simulation: using the controllability and purity of ultracold systems to simulate the physics and models from other areas of physics. The fermion simulation project has a vital role in providing computational validation of potential quantum simulators, before they are applied to large scale problems.

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Governance

Advisory Board

Our interactive science team includes two advisory boards with international and national members. The international board is made of leaders of key centres in the USA and Europe. It has, since 2003, helped us to build awareness of our activities around the world. The national board combine experience in both government and private enterprise and enhances our linkages with key stakeholders.

The national and international advisory Board have given high-level advice on the performance and challenges facing our research programmes. In addition, they have provided a broad international perspective on our future directions, through consultations on the proposed research programmes for a new ACQAO proposal in the next round of Centres of Excellence.

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Professor Keith Burnett, Vice-Chancellor, University of Sheffield, Sheffield UK.

Professor William Phillips, Nobel laureate, National Institute of Standards and Technology (NIST), Maryland, USA.

Professor Eugene Polzik, Niels Bohr Institute, Copenhagen, Denmark.

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Dr Bruce Whan, Director, Swinburne Knowledge, Swinburne University Of Technology.

Management

The main office of ACQAO is located at the ANU, were the Director, Hans Bachor, is responsible for the overall science direction and performance of the Centre. We regularly monitor our progress against the key performance measures (KPM) and international benchmarks. Our achievements measured as KPM's are described in detail on page 62. The Chief Operations Officer (COO), working alongside the Director, is responsible for all operational and financial aspects of the Centre. Our financial support comes from both the Australian Research Council (ARC) and the participating universities (ANU, UQ, SUT).

Throughout 2009 the Centre held a regular series of meetings as detailed in Figure 1. These meetings are an integral part of the Centre, covering the whole spectrum from the overall strategic direction of ACQAO to the daily management of our research activities. Fundamental decisions are determined by all Chief Investigators (CI) based on recommendations from the Executive and Advisory board. The Executive, which includes the Director, COO, Node Directors & Scientific Directors (Peter Drummond & Yuri Kivshar), supervises the ongoing administration.

Prof. Burnett visits ACQAO in April 2009

Figure 1. ACQAO meetings 2009

Centre Management Meetings			
Meeting style	People	Frequency	Location and Month
CI meeting	All CI's, Director & COO	Bi-annual	July, ANU, Canberra December, Adelaide, SA
Executive Committee	Research Director, COO, Node Directors & Scientific Advisors	Quarterly	March, July, September, November (by video conference)
Advisory Board	International & National members	Annually	International (by teleconference) – May, ANU, Canberra National – July, ANU, Canberra
International & National Workshop	Centre & Partners, other Australian groups	Bi-annual	February, Les Houches, France December, ACOLS, Adelaide
Individual Project & group	CI, Research Fellows, students & visitors	Fortnightly	Across the Nodes
IP Committee	Node Directors, Participating Universities	Annually	July, ANU, Canberra

ACQAO staff and students at the international workshop held in Les Houches

Coherent pulse sequencing with gradient echo memory

M. Hosseini[1], B. M. Sparkes[1], G. Hétet[1], J. J. Longdell[2], P. K. Lam[1], and B. C. Buchler[1]
[1] *Research School of Physics and Engineering, ACQAO, ANU*
[2] *Physics Department, University of Otago, Dunedin, New Zealand*

One possible paradigm for optical quantum state storage is to write the optical field onto the polarisation of an atomic ensemble. Provided the atomic states are long-lived, this allows to freeze light in space. By mapping the atomic polarisation back to an optical field, the light can be released at a later time. Significant progress has recently been made in implementing atomic quantum memory using electromagnetically induced transparency (EIT), photon-echo, off-resonant Raman, and other atom-light interaction processes [1].

Our coherent memory system, known as “Gradient Echo Memory” (GEM), can be used with two- and three-level atomic systems and in principle it can be 100% efficient without adding any extra noise to the stored light [2, 3]. The key to two- or three-level GEM is the application of an atomic frequency gradient along the length of the storage medium. Depending on the atomic system, a linearly varying electric or magnetic field can be used to induce a Stark or Zeeman shift that varies in the z direction, as shown in Fig. 1a. In the most simple storage protocol, a probe field is absorbed by the frequency shifted ensemble of atoms. Due to the frequency gradient in the ensemble, the Fourier components of the probe field are distributed linearly along on the z-axis [4]. The light is released by inverting the gradient as shown in Fig. 1b.

We have experimentally demonstrated in warm Rb vapour [5] that three-level GEM can be used to stretch and compress pulses (Fig. 1c), recall pulses in any desired order (Fig. 1d) and split pulses over multiple recall events (Fig. 1e). Recall efficiency of over 40% was also observed.

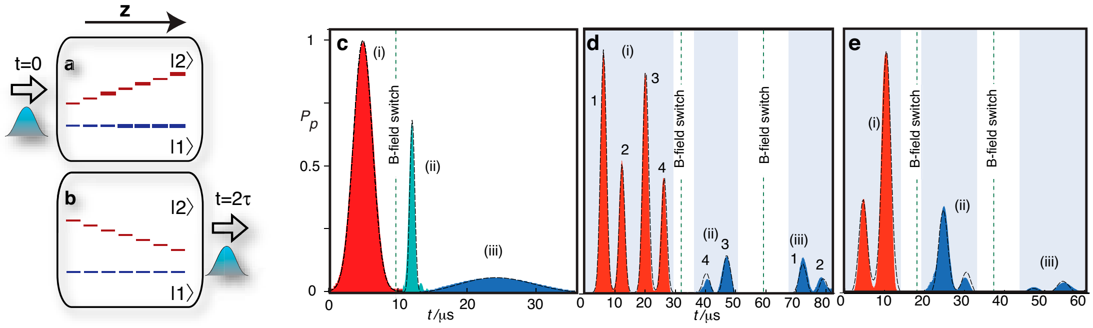

Fig. 1: (a) A pulse is absorbed in an ensemble. (b) Re-emission occurs after reversing the atomic frequency gradient. (c) Pulse compression (ii) and stretching (iii) of the input pulse (i). (d) Reordering of pulses. (e) Splitting of pulses. Pulse power (P_p) is in arbitrary units. The recalled pulses in (d) and (e) are magnified 10 times. The dashed lines show numerical models of the experiment. See [5] for details.

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High fidelity quantum memories with dynamical switching

Q. Y. He, M. D. Reid, and P. D. Drummond
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

We propose a digital approach to quantum memories using a single-mode oscillator-cavity model (Fig. 1(a)), in which the coupling is shaped dynamically in time to provide the optimum interface to an input pulse [1]. This concept, developed with partner investigator E. Giacobino in IFRAF (Paris) relies on the integration of a microscopic optical cavity with a long-lived quantum oscillator. The key new approach is a tailored gating pulse, which matches the memory to an input mode.

Our generic model is applicable to any linear storage medium ranging from a superconducting device to an atomic medium. In a subsequent paper, we derived a condition on the time-dependence of the oscillator-cavity coupling required to match to any external pulse-shape, including time-symmetric pulses (Fig. 1(b)). This contrasts with our previous work [1], in which the coupling was a step function resulting in non-symmetric pulses. Our digital quantum memory proposal is highly suitable for single qudit quantum information processing.

An essential feature of our treatment is that we show how a smooth, time-symmetric sech-pulse can be stored for times longer than the pulse duration, and recalled with high quantum fidelity. Thus, the output pulse shape replicates the input pulse. This type of quantum memory promises to give both high quantum fidelity and long lifetimes.

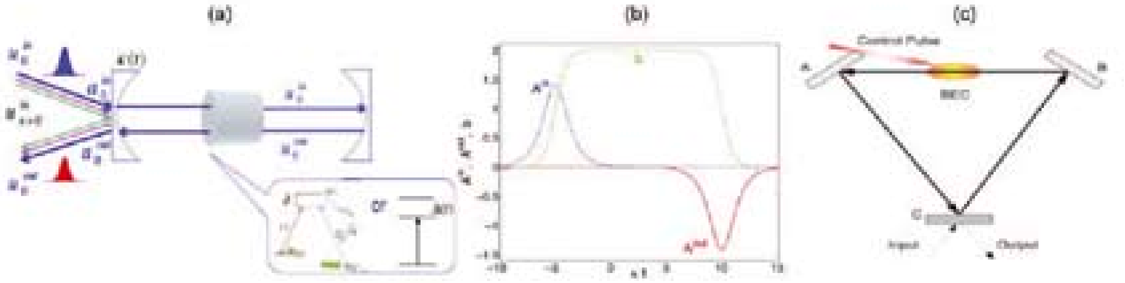

Fig. 1: (a) Proposed dynamical atom-cavity QM; (b) Cavity input (dashed) and output (solid) amplitudes [1]; (c) Setup for the memory with Bose-Einstein condensation [3].

The proposed architecture is very adaptable to many different technologies. These range from ultra-cold atomic gases at micro or nano-Kelvin temperatures through to superconducting circuits and even cooled nano-mechanical oscillators, which can approach the quantum domain. In principle, any of these can be utilized for the storage component inside the optical cavity. Currently, we are working on the storage of information in a trapped BEC [3]. The setup for the quantum memory is illustrated in Fig. 1(c). Here, we consider a BEC trapped in an optical cavity, which is continuously driven by a control laser. BEC in a cavity has been recently realized in experiments. This system results in very strong atom-photon coupling. This is extremely useful for performing quantum information processing before decoherence sets in. It also has the potential for new tests of quantum mechanics using entanglement of massive particles.

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Experimental demonstration of computer reconfigurable multimode entanglement

J. F. Morizur[1,2], L. Nicholls[1], P. Jian[1,2], S. Armstrong[1], K. Wagner[1],
M. T. L. Hsu[3], W. Bowen[3], N. Treps[2], J. Janousek[1], H.-A. Bachor[1]
[1] *Research School of Physics and Engineering, ACQAO, ANU*
[2] *Laboratoire Kastler Brossel, Paris Cedex 5, France*
[3] *School of Mathematics and Physics, ACQAO, UQ*

Novel quantum communication and computation protocols require an increasing number of entangled modes. Conventionally, the entangled modes are carried by many single mode beams [1]. In our work we demonstrate a set of tools that generate, manipulate and detect multimode entanglement within a single beam of light with the modes being set in the Hermite-Gauss basis. This new method is flexible and computer controlled in the sense that any quantum protocol requiring a finite number of modes can be tested. In our scheme (see Fig. 1), all the entangled modes are carried by a single beam and their correlations are measured with a pair of multipixel homodyne detectors and one single local oscillator. This method takes full advantage of the new degenerate OPAs which can squeeze simultaneously several co-propagating modes. It allows for fully computer controlled entanglement relationships: there is no need for hardware changes to switch from one protocol to another.

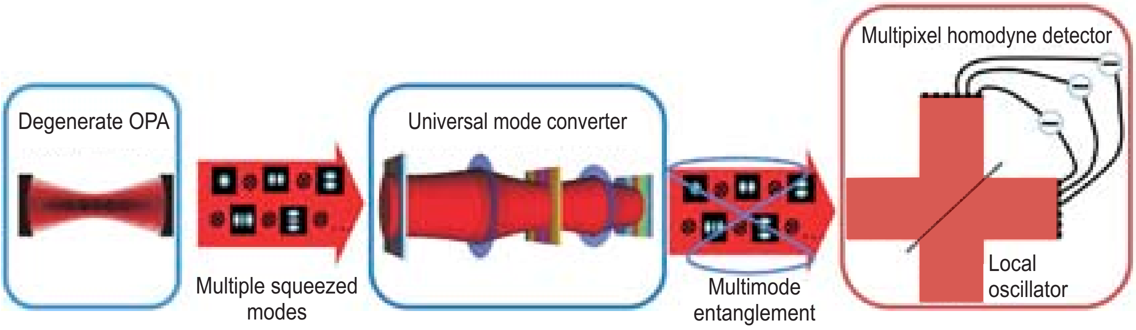

Fig. 1: Overview of the generation and manipulation of entanglement within a single beam of light.

The first step in creating the co-propagating, entangled modes is to generate several squeezed modes within the same beam. This can be done either by using a degenerate OPA cavity [2], which is a cavity capable of squeezing several Hermite-Gauss modes, or by combining orthogonal squeezed modes (produced by several single mode OPAs) with minimum loss using optical cavities. The second step is to mix the different squeezed spatial modes. For this purpose we introduce a unitary mode converter (UMC), which is a succession of spatial Fourier transforms and reflections on computer controlled deformable mirrors. We show that we can in theory perform any kind of spatial basis change provided that there are enough reflections and Fourier transforms [3]. Our experimental results for the performance of the UMC match well to the simulated results and outperform the conventional way of generating higher-order modes using optical cavities. Finally, the third step is a simultaneous detection which utilizes a pair of 8-pixel photodiodes working as a multi-pixel homodyne detector [4]. An 8-channel direct data acquisition card is then used to record the squeezing and determine the quantum correlations.

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Creating EPR-entangled matter beams

G. R. Dennis and M. T. Johnsson
Research School of Physics and Engineering, ACQAO, ANU

One of the most fundamental properties of quantum mechanics is non-locality. Although this property has been confirmed in ever more rigorous experiments, all such experiments have used photons, and never massive particles. Such a test is one of the holy grails of quantum atom optics. We have now identified a system and an experimental scheme which exhibits EPR entanglement between matter beams, the essential resource required for such a test.

The first hints came in a metastable helium (He*) atom laser experiment conducted by a group at the Australian National University. They coupled trapped atoms in a Bose-Einstein condensate (BEC) into an untrapped state, allowing them to form an atom laser and fall under gravity onto a detector which imaged the profile of the beam. At high coupling powers anomalous “peaks” were seen, well seperated from the expected atom laser profile. In simulations where the coupling was on resonance, only full quantum field theory simulations showed the peaks; semiclassical Gross-Pitaevskii simulations did not. This suggested there was a spontaneous vacuum seeding effect taking place. The mechanics of the process are shown in Fig. 1. An exotic form of four wave mixing occurs, with stationary trapped and untrapped atoms colliding and scattering into two beams along the long axis of the BEC.

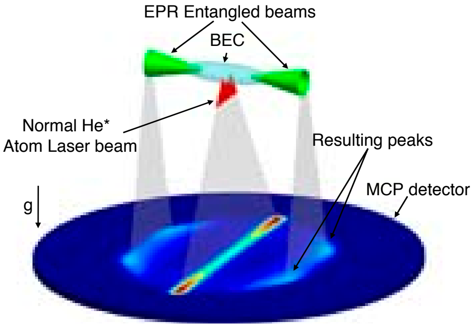

Fig. 1: Outcoupling an atom laser from a BEC with nonlinearity mismatches results in paired matter beams which can be EPR entangled.

While this appears to violate energy conservation, it is allowed due to the peculiar nonlinear energy terms in the He* system. For details see Dall *et al.* [1]. To investigate whether the twin beams were EPR entangled, we carried out a Bogoliubov analysis of the system. The mean fields which we linearized around were time-dependent, which would normally require a numerical solution, but we managed to prove that the mean fields were periodic, allowing us to apply a novel Floquet approach to gain analytic insight. We demonstrated that there are dynamic instabilities in the BEC which lead to exponential growth of fluctuations that couple opposite momenta. A high aspect-ratio BEC ensures that this amplification can only take place along the long axis of the condensate, leading to directed beams.

We showed that the evolution of the fluctuation operators for the two modes in the system were

$$\begin{aligned}\hat{\Lambda}(\mathbf{k},t) &= e^{i\omega(\mathbf{k})t}\left(\sinh(\gamma(\mathbf{k})t)\hat{\Lambda}'^{\dagger}(-\mathbf{k},0)+\cosh(\gamma(\mathbf{k})t)\hat{\Lambda}(\mathbf{k},0)\right),\\ \hat{\Lambda}'(\mathbf{k},t) &= e^{-i\omega(\mathbf{k})t}\left(\sinh(\gamma(\mathbf{k})t)\hat{\Lambda}^{\dagger}(-\mathbf{k},0)+\cosh(\gamma(\mathbf{k})t)\hat{\Lambda}'(\mathbf{k},0)\right),\end{aligned}$$

identical to degenerate parametric down conversion in optics. Just as PDC is a source of EPR-entangled photon pairs, the beams in our system are EPR-entangled atoms.

The manuscript describing these results in currently in preparation.

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Spatially inhomogeneous phase evolution of a two-component BEC

R. P. Anderson, C. Ticknor, M. Egorov, V. Ivannikov, A. I. Sidorov, and B. V. Hall
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

Accurate knowledge of the phase of matter waves is an important factor in studying BEC coherence, and its potential application to precision measurement. We observe the spatially dependent relative phase evolution of an elongated two-component Bose-Einstein condensate [1]. The pseudospin-$1/2$ system is comprised of the $|F=1, m_F=-1\rangle$ and $|F=2, m_F=1\rangle$ hyperfine ground states of ^{87}Rb, magnetically trapped on an atom chip [2] and interrogated via two-photon Ramsey interferometry. The first $\pi/2$ pulse prepares the pseudospin system in a non-equilibrium state. The subsequent evolution of each spin component leads to an inhomogeneous relative phase along the direction of weak confinement, varying by 2π across the condensate after $95\,\mathrm{ms}$ of evolution. The second $\pi/2$ pulse converts spatial variations of the relative phase into spatial variations of the longitudinal spin projection (Fig. 1). We observe Ramsey interference fringes whose decay ($1/e$ time $\sim 70\,\mathrm{ms}$) is due principally to the relative phase inhomogeneity, rather than decoherence or quantum phase diffusion. Our observations of the spatially dependent relative phase and subsequent loss of interferometric contrast are in striking agreement with simulations of the coupled Gross-Pitaevskii equations with decay terms corresponding to inter- and intra-state many body loss processes [1]. We have also demonstrated a new technique to simultaneously image each state, yielding sub-percent variations of the measured relative atom number, while preserving the spatial mode of each component.

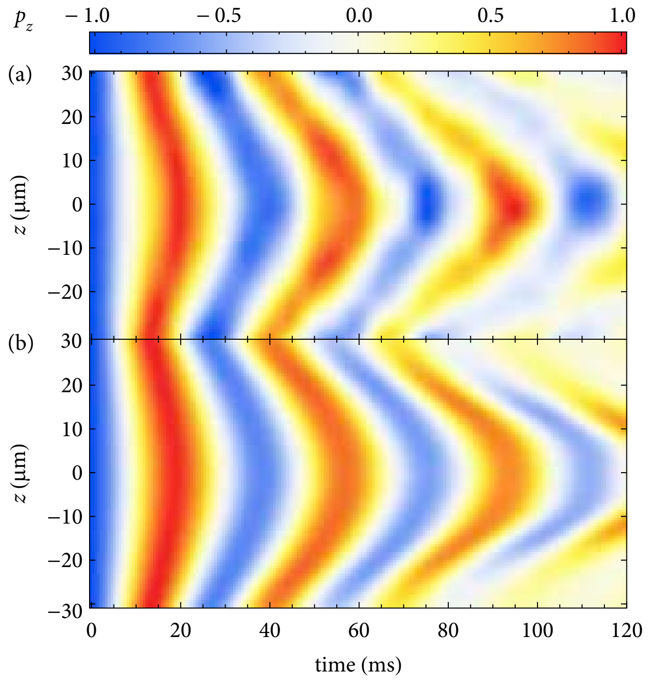

Fig. 1: Spatially resolved longitudinal spin projection of a pseudospin-$1/2$ BEC during Ramsey interferometry. Following the first $\pi/2$ pulse, the relative phase evolves inhomogeneously along the axial direction, z. This dephasing is manifest as spatial variation of the longitudinal spin projection, p_z, after the second $\pi/2$ pulse. (a) Experimental data, (b) coupled Gross-Pitaevskii simulation.

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Quantum projection noise limited interferometry with coherent atoms in a Ramsey type setup

D. Döring, G. McDonald, J. E. Debs, C. Figl, P. A. Altin, H.-A. Bachor,
N. P. Robins, and J. D. Close
Research School of Physics and Engineering, ACQAO, ANU

Atom interferometric devices are usually based on measuring the population in one of two atomic states. Every population measurement of an atomic two-level system is limited by what is known as the quantum projection noise limit [1, 2], and at any given flux it is the aim of a precision measurement to be limited by this fundamental noise limit instead of technical noise.

We present a quantum projection noise limited Ramsey type interferometer using freely propagating coherent atoms [3]. We couple two internal states of ^{87}Rb using two co-propagating Raman lasers. By scanning the frequency detuning of the two Raman lasers, we measure Ramsey fringes. The setup is an improved version of our previous Ramsey interferometer [4]. The main difference in an improved way of phase locking the two Raman lasers where we replaced the previous Mach-Zehnder type interferometer by an inherently stable Sagnac interferometer thus avoiding the need for external stabilization (see Fig. 1a). Fig. 1b shows the measured Ramsey fringes with a high visibility and noise of below 0.5% which corresponds to the quantum projection noise expected for our samples of 10^4 atoms. This experiment will pave the way towards observing squeezing effects in an atom laser, allowing for the achievement of improved sensitivity in atom interferometers surpassing the quantum projection noise limit.

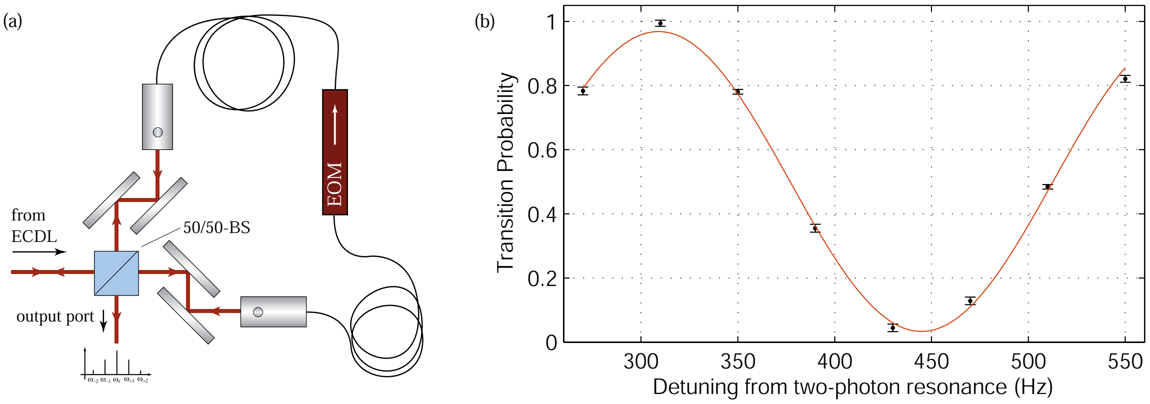

Fig. 1: Schematic of Sagnac interferometer (a). The resulting laser beam acts as a beam splitter for the atoms. ECDL: extended cavity diode laser. EOM: electro-optic modulator. BS: beam splitter. Measured Ramsey fringe (b).

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Universal structure of a strongly interacting Fermi superfluid

H. Hu, E. D. Kuhnle, X. J. Lui, P. Dyke, M. Mark, P. D. Drummond, P. Hannaford, and C. J. Vale
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

Universality is a remarkable property of strongly interacting systems of fermions. For sufficiently strong interactions, all dilute Fermi gases behave identically on a scale given by the average particle separation. Ultracold Fermi gases in the Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) superfluid crossover display such universality, although their universal properties are not exactly known. In 2005 Shina Tan [1] developed several elegant exact relations for the BEC-BCS crossover, which connect the bulk thermodynamic properties to the microscopic parameters using a single short-range parameter known as the contact, $\mathcal{I}$.

Using Tan's result for the pair correlation function, we have derived a universal relation for the spin-up/spin-down static structure factor, $S_{\uparrow\downarrow}$, of a Fermi gas in the BEC-BCS crossover [2].

$$S_{\uparrow\downarrow}(q >> k_F) = \frac{\mathcal{I}}{4Nk_F}\frac{k_F}{q}\left(1 - \frac{4}{\pi q a}\right), \tag{1}$$

where N is the atom number, k_F is the Fermi wavevector, q is the momentum and a is the s-wave scattering length. Apart from some factors which we can easily determine, this depends only on the dimensionless contact $\mathcal{I}/Nk_F$. We have previously shown how $S_{\uparrow\downarrow}(q >> k_F)$ can be measured with high momentum transfer Bragg spectroscopy [3].

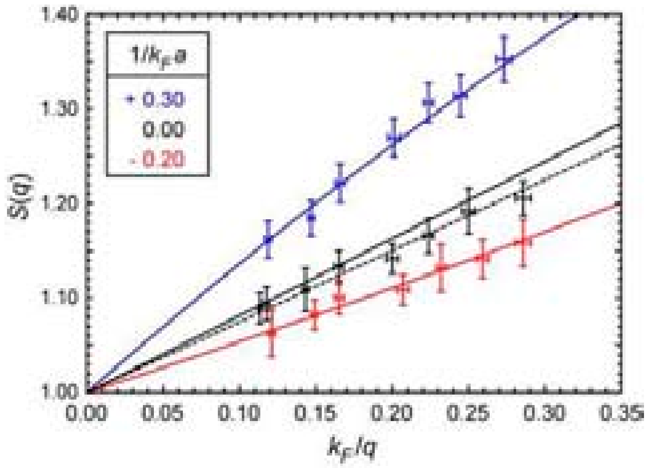

Figure 1: Universal behaviour of the static structure factor of a strongly interacting Fermi superfluid

We have performed Bragg spectroscopy on a strongly interacting ultra-cold ^{6}Li Fermi gas in a balanced mixture of the lowest two spin states to test Eq. (1). To extract the absolute value of the static structure factor we integrate measured Bragg spectra over all Bragg frequencies and normalise them according to the f-sum rule [2]. Multiple Bragg spectra are taken at three different values of the dimensionless interaction parameter $1/(k_F a)$ = 0.3, 0.0, -0.2, and $S(q)$ is plotted versus k_F/q. The data closely follow the exact prediction shown by the solid lines. The dashed line is a straight line fit to the unitarity data which has a slope of 0.75 ± 0.03, slightly below the $T = 0$ prediction of 0.81, due to reduced pairing at finite temperature.

Our new Tan relation is seen to accurately describe $S(q)$ on both sides of the Feshbach resonance. Pair correlations are not only universal but follow a simple power law dependence. These results verify Tan's predictions linking microscopic and bulk properties of these gases and provide the first measure of the contact $\mathcal{I}$.

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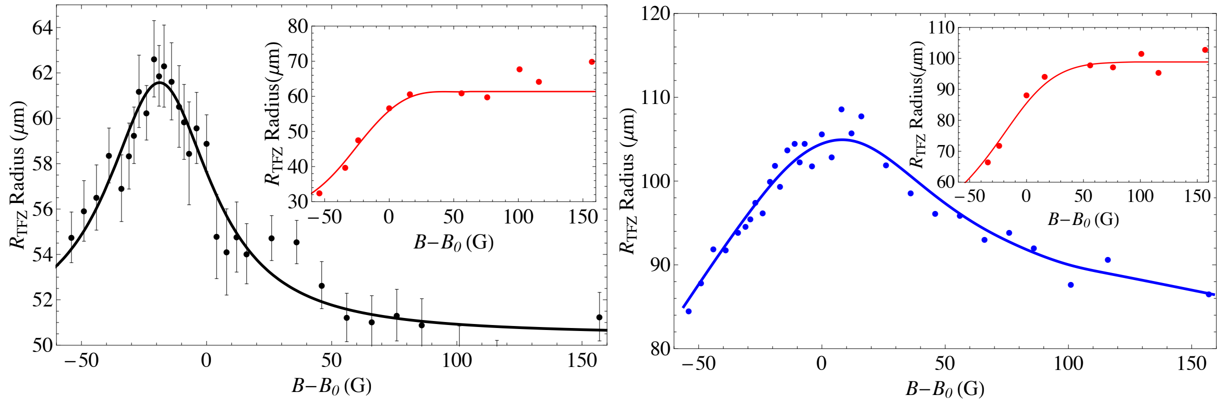
Quasi Two-Dimensional ^{6}Li Fermi gas

P. Dyke, E. D. Kuhnle, M. Mark, P. Hannaford, and C. J. Vale
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

Two-dimensional Fermi gases can behave in surprisingly different ways from their three-dimensional counterparts. This becomes particularly important for a two-component Fermi gas in the Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) crossover region, where the 3D scattering length is widely tunable. In 2D, bound states can exist even on the BCS side of the Feshbach resonance. In quasi-2D other effects in the scattering become important, one example is a confinement induced resonance (CIR). Recently Haller *et al.* [1] observed of a CIR in a 1D Bose gas. A pole in the scattering amplitude occurs when the transverse oscillator length $a_\perp = \sqrt{\hbar/m\omega_\perp}$ (where m is the mass and $\omega_\perp$ is the axial trapping frequency) becomes equal to the 3D s-wave scattering length a_{3D}, and colliding atoms can resonantly form molecules in the first excited state.

To form a 2D Fermi gas we must satisfy $k_B T, E_F < \hbar\omega_\perp$. In our experiments, a 2D optical trap is formed by a light sheet produced by tightly focusing a circular Gaussian beam in one direction with a cylindrical lens. The trapping frequencies are $\omega_\perp/2\pi \approx$ 4 kHz and $\omega_r/2\pi \approx$ 70 Hz in the tightly and weakly confined directions respectively, giving an aspect ratio of ~60. For an ideal Fermi gas, $E_F < \hbar\omega_\perp$ for $N \lesssim$ 2000 is necessary to achieve the 2D regime.

We have observed reduced dimensionality by measuring the transverse cloud width across the Feshbach resonance after a short time of flight. The width shows a peak at 816 G (Fig. 1a) for an atom number of ~4000. The inset shows the width of a 3D cloud vs. magnetic field which displays the usual monotonic increase from the BEC to BCS limits. We interpret the increase in the 2D case as arising from the production of molecules in excited transverse modes which expand more quickly upon release, as expected for a confinement induced resonance. At large N (Fig. 1b) the width in the 2D case shows a broader peak at a higher field but is still vastly different from the 3D case (inset). This we believe to be due to higher transverse excited states being populated through collisions but we are yet to quantitatively model these experiments. Our goal is to understand how CIRs affect pairing and superfluidity in lower dimensional Fermi gases.



(a) (b)

Fig. 1: Observed width of a quasi-2D Fermi gas after expansion for (a) $N = 4000$ atoms and (b) $N = 10^5$ atoms. Insets show the corresponding widths after expansion from our regular 3D optical trap. Solid lines are a guide to the eye.

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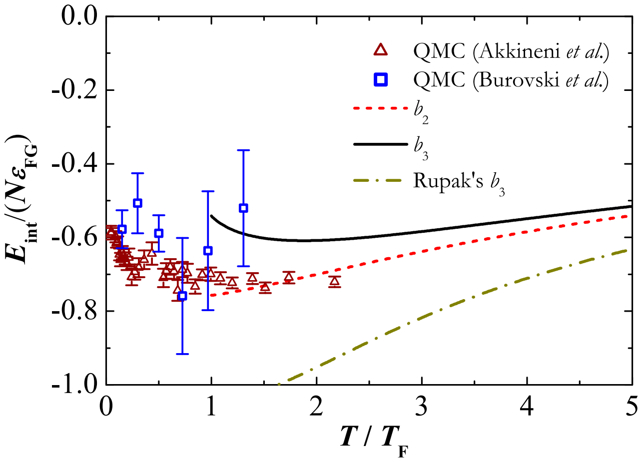
Strongly Interacting Fermi Gases

X.-J. Liu, H. Hu, and P. D. Drummond
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

Stongly correlated Fermi gases are of wide interest. They pose many unanswered questions in quantum many-body systems, ranging from neutron stars, hadrons, and quark matter through to high T_c superconductors. Recent investigation of Feshbach resonances in ultracold atomic Fermi gases have opened new, quantitative opportunities to address these challenges. However, a profound understanding is plagued by the large interaction strength, for which the use of perturbation theory requires infinite order expansions.

At temperatures above the transition temperature we are able to use a reliable virial expansion method, which allows a controllable study of the thermodynamics of stongly correlated Fermi gases near the BEC-BCS crossover region [1,2]. Our theoretical prediction for the third order coefficient was completely different to previously predicted values. It has now been experimentally confirmed to high accuracy by Salomon's group at ENS [3]. Further, an important challenge in ultracold superfluid gases is to observe second sound. We approached this problem in a trapped unitary Fermi gas by solving the Landau two-fluid equations [4]. Our result has stimulated an experimental group at Innsbruck to set up an experiment to measure second sound.

Virial Expansion for a Strongly correlated Fermi Gas



We proposed a practical way to study strongly interacting Fermi gases, by determining the virial expansion coefficients for both harmonically trapped and homogeneous cases. We calculated the third order coefficient at finite temperatures, obtaining a radically different result to an earlier calculation by Rupak. At resonance, we obtain the T-independent coefficient, $b_3^{hom} \approx -0.29095295$. Our prediction has been confirmed by experiments carried out by international partner investigators at ENS (IFRAF), Paris.

Second Sound in a Trapped Fermi Gas

Using a variational approach, we solve the equations of two-fluid hydrodynamics in a unitary Fermi gas trapped by a harmonic potential. We show that the density fluctuations (first sound) weakly couples to the entropy fluctuations (second sound) of the system, giving rise to a typical hybridization effect where the frequencies cross. We predicted the value of the frequency splitting caused by hybridization and show how the coupling results in a beating in the density response. This gives a promising way of exciting and detecting second sound in this system.

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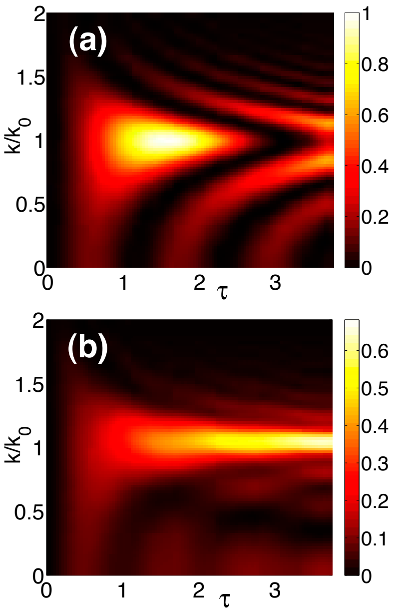
Exact Quantum Dynamics of Fermionic systems

M. Ögren, K. V. Kheruntsyan and J. F. Corney
School of Mathematics and Physics, ACQAO, UQ

The physics of interacting fermions is the basis of many of the most important phenomena in condensed matter physics, ultracold gases, and quantum chemistry. A fundamental issue is how the microscopic interactions at the quantum level give rise to collective and emergent effects in many-body systems. Ultracold quantum gases provide an ideal platform on which to explore such issues, through highly controllable implementations of analogue many-body systems for which the dynamical evolution and correlations are directly accessible. In order to make predictions from the underlying theory and to validate the potential simulators, or to benchmark approximate approaches, a numerical simulation of the exact real-time dynamics is required.

To this end, we are adapting the Gaussian phase-space representation for fermions to dynamical simulations of large scale systems. This representation was used to give a sign-free simulation method for determining the ground-state properties of the Hubbard model, thereby giving insight into the origin of high-T$_c$ superconductivity in cuprates [1]. By contrast, we are focussing on the *real-time* dynamics of many-body quantum systems, a class of problems for which few practical exact methods exist.



Time-evolution of atomic momentum densities in (a) Pauli-blocked and (b) depleted regimes.

For the first application of the fermionic phase-space method to a multimode dynamical problem [2], we consider the dissociation into pairs of correlated fermionic atoms of a uniform molecular BEC (MBEC) initially in a coherent state at zero temperature. Assuming sufficiently low densities, we neglect s-wave scattering interactions to simplify the treatment. We simulated systems with $M = 10^3$ relevant atomic Fourier modes and $N_0 = 10^2 - 10^4$ ($^{40}K_2$) molecules at densities $n_{1D} \simeq 1.3 \times 10^5 - 1.3 \times 10^7$ m^{-1}. In these cases, the number-state calculation is impossible as the dimension of the Hilbert space is enormous ($d = 2^M n_{\max} \gg 10^{300}$). We find different regimes of dynamical behaviour: (a) if the initial number ($N_0 = 10^4$) is much larger than the number of available atomic modes, the dynamics is dominated by Pauli blocking and is well-described by a pairing mean-field theory; (b) if the number of molecules is comparable (or less) than the number of available modes, we see large molecular depletion and the development of strong correlations. In this regime, the atom pairs develop beyond-mean-field correlations, in addition to becoming correlated with the molecular field, leading to large fluctuations in the second-order correlation function of the molecules.

Although we have here reported only on 1D simulations, we have also implemented 2D and 3D calculations and found that the method works reliably in higher dimensions. Extensions of the method to implement s-wave scattering interactions will enable the study of non-equilibrium dynamics in a broader class of fermionic systems of current experimental interest, such as atomic Mott insulators in optical lattices and the BCS-BEC crossover problem.

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Macroscopic quantum self-trapping of ultracold Bose-Fermi mixtures

E. A. Ostrovskaya, S. F. Caballero-Benitez, and Yu. S. Kivshar
Research School of Physics and Engineering, ACQAO, ANU

Self-trapping phenomena are among the most dramatic effects of atomic interactions in the systems of quantum degenerate gases. The so-called *macroscopic quantum self-trapping* (MQST) effect manifests itself as localization of most of the particles in the system in a particular region in space. The MQST and related effects in purely bosonic systems have been extensively analyzed in different physical contexts, from the Josephson effect in superconductors and the study of superfluid ^{4}He to the alkali Bose-Einstein condensates. The MQST effect in a so-called Bose-Josephson junction, i.e. a Bose-Einstein condensate loaded into a double-well potential, has been extensively studied theoretically [1] and observed experimentally [2]. Its appearance is linked to the formation of new stationary states that are characterized by a population imbalance between the wells of the trapping potential, which becomes more pronounced with growing nonlinearity. Moreover, it turns out that the MQST effect plays an important role in the dynamics of condensates in periodic potentials, leading to the formation of self-trapped or truncated gap states [3].

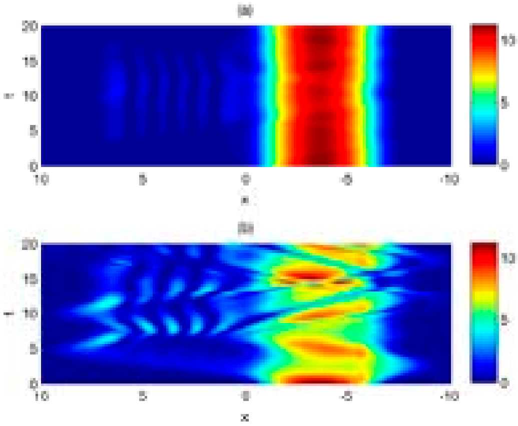

Fig. 1: Dynamical suppression of MQST regime in the case of repulsive inter-species interactions. Shown are the densities of the bosonic component at (a) zero and (b) non-zero concentration of fermions.

In the context of ultracold Bose-Fermi gases, we have analysed theoretically the effect of degenerate fermions on the self-trapping behavior of ultracold bosons in a quasi-one dimensional symmetric double-well potential [4]. In order to analyze the static properties of the system, we used a self-consistent numerical approach, as well as a quasi-analytical treatment, based on a mean-field density approximation for the fermionic component and a coupled-mode theory for the bosonic component. We considered both attractive and repulsive interactions between bosons and fermions, and found that, depending on the type of the inter-species interactions, a significant enhancement or suppression of the MQST regime can occur in the system (see Fig. 1). Both the enhancement and the suppression of self-trapping in the BEC cloud mixed with degenerate fermions may signal the existence of the new regimes of the dynamics and switching of BECs in atomic waveguides and nonlinear interferometers with mixed atomic species.

They are also expected to have profound consequence for the formation and dynamics of the self-trapped gap states in the Bose-Fermi mixtures loaded into periodic potentials. Beyond the mean field, these effects may have an implication for the onset of the superfluid to Mott insulator (MI) transition in a lattice potential, leading to the inhomogeneous suppression of the MI regime in the case of repulsive interaction and phase separation.

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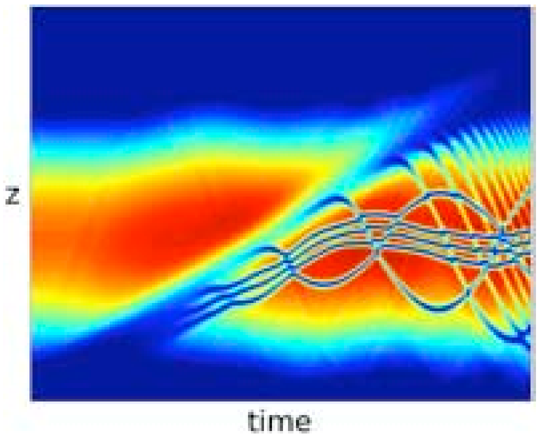
Superfluidity in dilute gas Bose-Einstein condensates

A. G. Sykes[1], C. Feng[1], D. C. Roberts[2], A. S. Bradley[3], B. P. Anderson[4], and M. J. Davis[1].
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *Center for Nonlinear Studies, Los Alamos National Laboratory, New Mexico, USA*
[3] *Jack Dodd Centre for Quantum Technologies, University of Otago, Dunedin, New Zealand*
[4] *College of Optical Sciences, University of Arizona, Tucson, Arizona, USA*

It is generally accepted that dilute gas Bose-Einstein condensates (BECs) in three dimensions are superfluids — they can flow without resistance below a certain critical velocity, and may only rotate by forming quantised vortices. In the past twelve months we have been investigating a number of aspects of superfluidity in ultra-cold Bose gases.

1. A recent experiment by the Engels group at Washington State University has observed evidence for a superfluid critical velocity in dragging both attractive and repulsive obstacles through a harmonically trapped, cigar-shaped BEC [1]. In 2009 we have completed the modelling of these experiments using the 3D Gross-Pitaevskii equation and have found that it is highly likely that their data should not be interpreted as demonstrating a threshold velocity for the loss of superfluidity [2]. The image to the right is a plot of the average density in space and time of an obstacle being forced through a BEC showing soliton formation in its wake.



2. Recent experiments in the Anderson group at the University of Arizona have observed the formation of vortex dipoles by forcing a highly oblate BEC past a small Gaussian obstacle formed by a tightly-focussed blue-detuned laser beam. The dipole formation only occurs above a certain critical velocity, measured to be about 170 μm/s. At higher velocities multiply-charged dipoles are formed, which have not been predicted previously. We have simulated these experiments at zero and finite temperature and found good agreement with the observations [3].

3. Previous work using perturbation theory 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 [4], in contradiction with the conventional understanding of superfluidity. We have performed a mostly analytic calculation that finds a non-zero force acting on a delta-function impurity moving through a quasi-one-dimensional Bose-Einstein condensate at all subcritical velocities and at all temperatures. The force occurs due to an imbalance in the Doppler shifts of reflected quantum fluctuations from either side of the impurity [5]. It is feasible to numerically simulate this system, and we are continuing with quantum dynamical calculations aimed at conclusively demonstrating this force dynamically in a finite system.

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Formation of topological defects in Bose-condensed gases

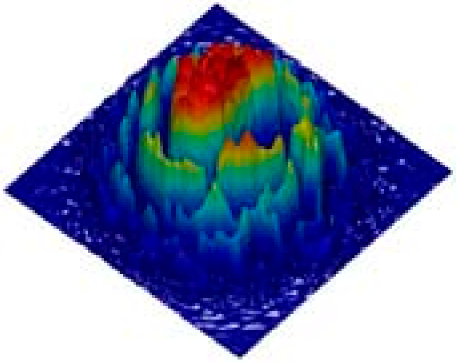
J. Sabbatini[1], G. M. Lee[1], S. A. Haine[1], A. S. Bradley[2], B. P. Anderson[3], and M. J. Davis[1].
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *Jack Dodd Centre for Quantum Technologies, University of Otago, Dunedin, New Zealand*
[3] *College of Optical Sciences, University of Arizona, Tucson, Arizona, USA*

Quenches of quantum degenerate Bose gases are expected to result in the formation of topological defects such as solitons, vortices, or domain walls depending on the particular system. This project aims to simulate such quenches using the stochastic Gross-Pitaevskii formalism at finite temperature and the truncated Wigner method at zero temperature [1] to understand the formation and subsequent evolution of the defects [2].

1. We have continued the study of the formation of vortices in evaporatively cooled Bose-Einstein condensates [3]. Over the past twelve months we have focussed on the development of first and second order coherence, and the origin of the vortices from the apparently turbulent initial stages of condensation. We are aiming to develop an experimental scheme that would for the first time experimentally demonstrate the predicted Kibble-Zurek scaling of the number of defects with the quenching rate in a highly oblate trap [2].

2. Quench cooling and condensate formation experiments have recently been performed in a cigar-shaped trapping potential in the Engels group at Washington State University, and have observed what appear to be dark solitons in the density profile. This year we have simulated a one dimensional version of this experiment, and indeed observe the appearance of solitons during condensation. We have developed a robust algorithm for the detection of solitons, and tracked their evolution as equilibrium is attained [4].

3. We have established a quantum Kibble-Zurek scenario in a two-component BEC that is naturally immiscible [5]. By turning on a coupling between two hyperfine states of a BEC it is possible to load the system into a dressed state which is miscible (i.e. spatially homogeneous.) By ramping off the coupling the system returns to the immiscible state, with faster ramps resulting in more domain walls forming between the two components. We have demonstrated a power law scaling of the number of domain walls in a both a 1D homogeneous and 1D trapped system, but with different exponents. The figure shows the 2D density of one of the components after the coupling is turrned off.



4. The first experiment observing spontaneous symmetry breaking in a spinor BEC was performed in the Stamper-Kurn group at Berkeley [6]. Over the past year we have been performing quantitative simulations of the quantum dynamics of this experiment in a effort to understand the experimental data on correlations and number of defects. In particular we wish to understand the details of quantum and thermal noise in the initial state.

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Spontaneous Four-Wave Mixing of de Broglie Waves: Beyond Optics

V. Krachmalnicoff[1], J.-C. Jaskula[1], M. Bonneau[1], G. B. Partridge[1], D. Boiron[1],
C. I. Westbrook[1], P. Deuar[2], P. Ziń[3], M. Trippenbach[4], and K. V. Kheruntsyan[5]
[1] *Laboratoire Charles Fabry, Institut d'Optique, Univ Paris Sud, CNRS, Palaiseau, France*
[2] *Institute of Physics, Polish Academy of Sciences, Warsaw, Poland*
[3] *The Andrzej Sołtan Institute for Nuclear Studies, Warsaw, Poland*
[4] *Institute of Theoretical Physics, Physics Department, University of Warsaw, Poland*
[5] *School of Mathematics and Physics, ACQAO, UQ*

We investigate the atom-optical analog of degenerate four-wave mixing of photons by colliding two Bose-Einstein condensates (BECs) of metastable helium and measuring the resulting momentum distribution of the scattered atoms with a time and space resolved detector [1, 2]. For the case of photons, phase matching conditions completely define the final state of the system, and in the case of two colliding BECs, simple analogy implies a spherical momentum distribution of scattered atoms. We find, however, that the final momenta of the scattered atoms instead lie on an ellipsoid whose radii are smaller than the initial collision momentum. Numerical and analytical calculations agree well with the measurements, and reveal the interplay between many-body effects, mean-field interaction, and the anisotropy of the source condensate.

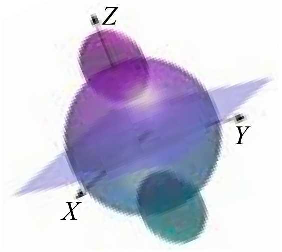

Fig. 1. Schematic diagram of the collision geometry.

In Fig. 1 we show the schematic diagram of the collision geometry in the center-of-mass frame in which we denote the collision axis as Z. The two disks represent the colliding condensates in momentum space. The sphere represents the halo of scattered atoms. The axial direction of the initial, cigar-shaped condensate is along X. We analyze the experimental and theoretical data in the XY-plane. In Fig. 2 (a) we show a slice of the experimentally detected scattering halo in the XY-plane that reveals its annular structure; in Fig. 2 (b) we show the respective theoretical result obtained from the first-principles simulations using the positive-P method.

Fig. 2 (c) shows the comparison of the experimental (black) and theoretical (red) data for the peak radius of the scattering halo on the equatorial plane versus the azimuthal angle ϕ; as we see the results agree within $\sim 2\%$ of accuracy. We have also analyzed the problem using a stochastic implementation of the Bogoliubov approach, which allows us to identify and illustrate the contributions of various mean-field interaction effects in the scattering process.

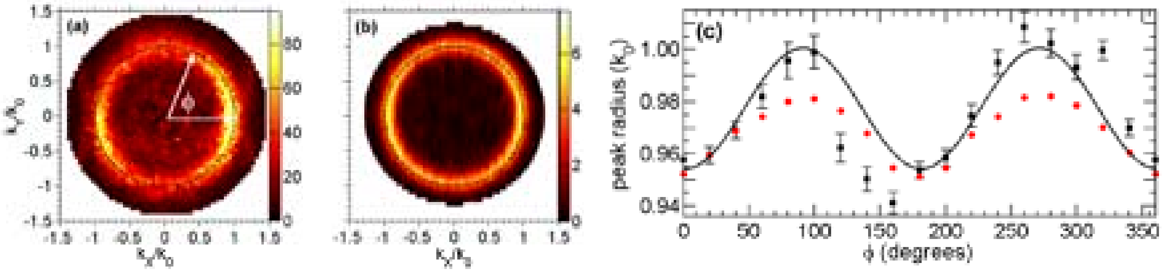

Fig. 2. (a) Momentum space density $n(k_X, k_Y)$ (in arb. units) of the experimentally observed scattering halo on the equatorial plane; (b) Same as in (a) but from the positive-P simulation after 70 μs collision time, in units of 10^{-18} m^3. (c) Peak radius versus the azimuthal angle ϕ.

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New tests of quantum mechanics: entanglement, EPR and Bell

M. D. Reid[1], Q. Y. He[1], H.-A. Bachor[2] , E. Cavalcanti[3], and P. D. Drummond[1]
[1] *Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT*
[2] *Research School of Physics and Engineering, ACQAO, ANU*
[3] *Center for Quantum Dynamics, Griffith University*

In 2009 we developed a number of novel tests of quantum entanglement, the Einstein-Podolsky-Rosen paradox and the Bell inequality, related to the famous nonlocality of quantum mechanics, leading both to novel scientific tests and potential quantum technologies.

Entanglement transfer between qubits was studied [1], thus demonstrating how entanglement can be treated as a mobile resource which can be communicated from one system to another. The goal of this work, treated in a subsequent paper [2], was to show how entanglement can be treated as a conserved quantity, like energy. Subsequent joint work with Griffith University investigated the relationship between the EPR paradox and a related concept called quantum steering. This work developed practical benchmarks for the demonstration of generalized steering [3].

Next, a high impact letter publication appeared in Physical Review Letters [4] which developed a completely new approach to quantum information with continuous variables. The new feature was the idea of a functional inequality, which introduced the concept of using arbitrary functions of measurements as a novel means of storing or manipulating quantum information. In this case, the payoff is a Bell violation with much greater resistance to loss and decoherence.

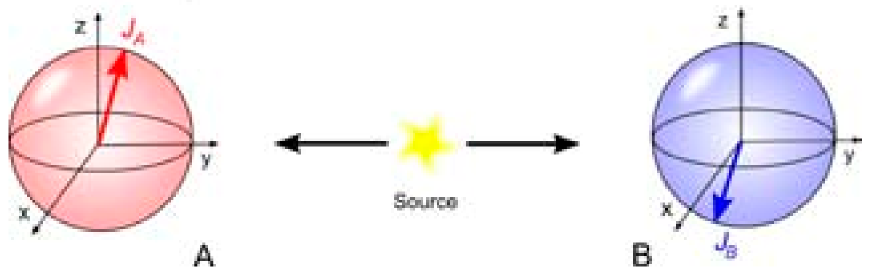

Fig. 1: Diagram of correlated spin tests with Bose-Einstein condensation [5, 6].

It is often important to be able to communicate quantum information using spinor variables. In a joint inter-node study [5], we analysed a general approach to spinor quantum information, in terms of robustness against loss. This was extended to arbitrary spin quantum numbers, which is essential for treating EPR and Bell inequalities in Bose-Einstein condensates. Finally, in a development involving both internode cooperation and several ACQAO partners, we published a major review on the Einstein-Podolsky-Rosen paradox [6]. This is a major review article in the most prestigious and highest impact journal in physics. It represents the first review in the history of the EPR paradox to treat all major experimental and theoretical studies.

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Optical entanglement of co-propagating modes

J. Janousek[1], K. Wagner[1], J. F. Morizur[1,2], N. Treps[2], P. K. Lam[1], C. C. Harb[3], and H.-A. Bachor[1]
[1] *Research School of Physics and Engineering, ACQAO, ANU*
[2] *Laboratoire Kastler Brossel, Paris Cedex 5, France*
[3] *Australian Defence Force Academy, Canberra, Australia*

Optical entanglement is a key requirement for many quantum communication protocols. Conventionally, entanglement is formed between two distinct beams, with the quantum correlation measurements being performed at separate locations. Such setups can be complicated, requiring the repeated combination of complex resources, a task that becomes increasingly difficult as the number of entangled information channels, or modes, increases. We pave the way towards the realization of optical multimode quantum information systems by showing continuous variable entanglement between two spatial modes within one beam [1], see Fig. 2. Our technique is a major advance towards practical systems with minimum complexity. We demonstrate three major experimental achievements. First, only one source is required to produce squeezed light in two orthogonal spatial modes. Second, entanglement is formed through lenses and beam rotation, without the need for a beamsplitter. Finally, quantum correlations, see Fig. 1, are measured directly and simultaneously using a multipixel quadrant detector.

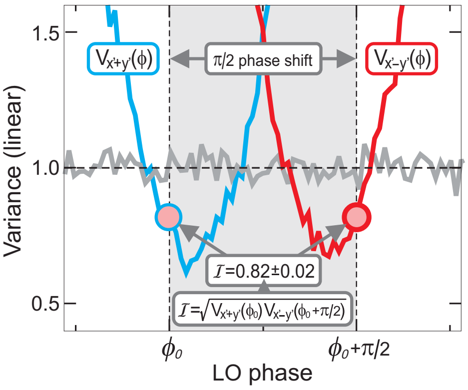

Fig. 1: Results for inseparability. Measurement of the variance for the sum $V_{x'+y'}(\phi)$ and difference $V_{x'-y'}(\phi)$ for the 45° rotated fields. The data, both below the QNL, are combined to one value for the inseparability of $\mathcal{I} = 0.82 \pm 0.02$, demonstrating significant entanglement between two orthogonal spatial modes within one optical beam.

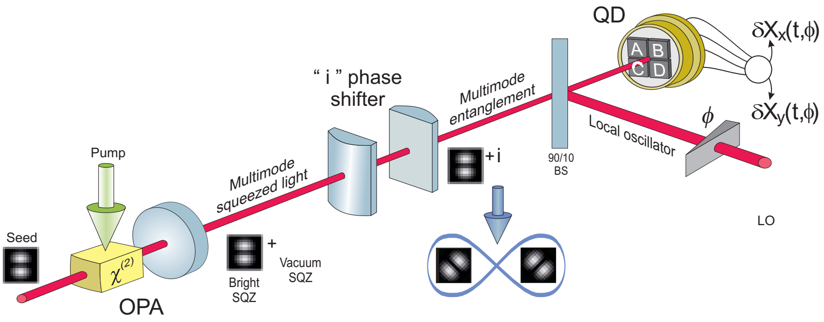

Fig. 2: Multimode entanglement experimental setup. We use a degenerate OPA for generating two squeezed higher-order modes. An optical system made of cylindrical lenses imparts a $\pi/2$ phase shift on one of the modes. Entanglement between 45° rotated spatial modes is analyzed using a QD set to a correct basis. $\delta X_x(t,\phi)$ is equivalent to $\delta X_{(A+B)-(C+D)}(t,\phi)$, and $\delta X_y(t,\phi)$ is given by $\delta X_{(A+C)-(B+D)}(t,\phi)$. OPA: optical parametric amplifier; LO: local oscillator; HD: homodyne detection; QD: quadrant detector.

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EPR entanglement in asymmetric systems

K. Wagner[1], J. F. Morizur[1,2], S. Armstrong[1], J. Janousek[1], P. K. Lam[1], and H.-A. Bachor[1]
[1] *Research School of Physics and Engineering, ACQAO, ANU*
[2] *Laboratoire Kastler Brossel, Paris Cedex 5, France*

Entangled beams of light have been proposed for use as a resource in many quantum systems. One experimental challenge encountered in continuous variable optical entanglement is the inevitable existence of losses in the system, which ultimately degrade the entanglement that can be used and measured. The deterioration of the entangled state when losses exist in different parts of the experiment is discussed. Two different measures of entanglement, inseparability and EPR entanglement, are compared.

We present work on optimizing biased entanglement, where one squeezed beam is mixed with a vacuum mode to produce an entangled state [1]. EPR entanglement that results from this method is of interest to Quantum Key Distribution (QKD) systems, where one party (Bob) tries to predict the data sent by another party (Alice). QKD establishes a secure key for sending encrypted information between these two parties. Such schemes, in the continuous variable regime, originally required a line loss of less than 50 % [2]. This limitation has since been overcome with post-selection protocols, and by the use of reverse reconciliation [3]. Nevertheless, an improvement of EPR correlations for a given amount of loss in a system is useful, as it can lead to an increase in the rate at which the key and subsequent information can be transferred.

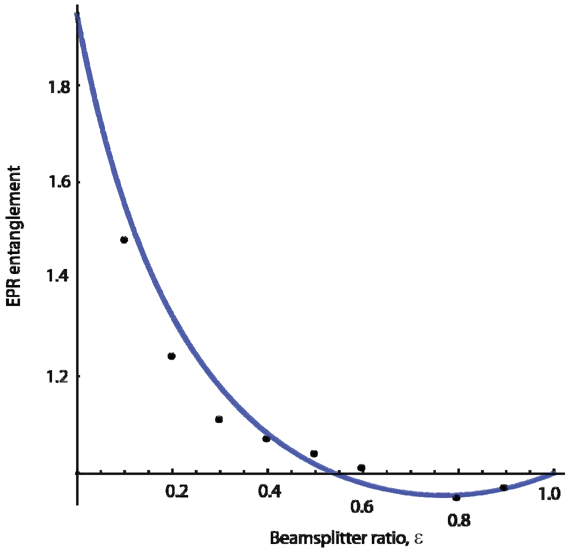

Fig. 1: EPR entanglement in one direction for a biased entanglement setup. There is no entanglement for a conventional 50:50 beamsplitter, but entanglement is achieved using an 80:20 beamsplitter.

We investigate the effect of changing the beam-splitting ratio in a biased entanglement setup. We compare our experimental and theoretical results, and find the optimal EPR entanglement for a given set of losses in the system as we change the mixing ratio. We consider losses in two different places in the setup - losses on the beam before the beam-splitter is encountered, and losses on one arm after the splitting. Losses before the beam-splitter always occur, to some extent, in the squeezed beam, and the losses on one arm of the entanglement correspond to a line loss in a data transfer system.In a biased entanglement setup, the optimal beamsplitter ratio is given by $\epsilon = \frac{1}{2\eta}$, where η is the transmission before the beamsplitter. For the case where losses exist both before the beamsplitter, and on one arm of the entanglement, there is also an optimum ratio that can occur away from the 50/50 ratio normally used. Using this, we measured biased EPR entanglement for losses that would normally prevent it from being measured.

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Squeezing the most out of your atom laser:

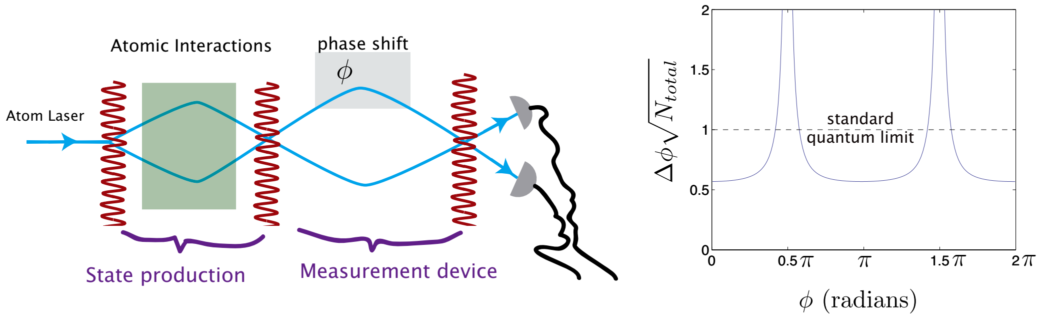
What is the best way to squeeze an atom laser for precision measurement?

S. A. Haine[1], M. T. Johnsson[2], and J. C. Close[2]
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *Research School of Physics and Engineering, ACQAO, ANU*

An atom laser is a device which produces a matterwave with a well defined frequency, amplitude, and phase. Atom lasers, when used as the source for an atom interferometer, show promise for increased sensitivity of electric, magnetic, and gravitation fields, as well as rotations and accelerations. The use of massive particles over photons offers the possibility of many orders of magnitude increase in the sensitivity of these devices, due to the slower propagation speed of atoms. However, as the flux of these devices is limited, quantum noise will set a fundamental limit to the sensitivity that these devices can achieve. For classical sources, this limit is $\Delta\phi = 1/\sqrt{N}$ [1].

A way to get around this limit is to use nonclassical states, such as squeezed states and entangled states. We have previously proposed two schemes for producing squeezed and entangled atom lasers. The first of these schemes relied on the transfer of the quantum state of an optical beam to an atomic beam, and the second scheme used the nonlinear atomic interactions and atomic interference to create squeezed states. However, the quantum states which are easiest to create and observe nonclassical effects in, are not necessarily the best for increasing the sensitivity of phase measurements. We have been investigating how best to use these techniques to enhance the sensitivity of phase measurements.

Naively one might assume that the atom-atom interactions do nothing but degrade the sensitivity of a phase measurement, as this interaction leads to phase diffusion. However, by careful choice of parameters, including the beamsplitter ratios, this phase diffused state can be transformed into a state with relative phase squeezing, which leads to an enhancement in the sensitivity of phase measurements. This is analogous to optical homodyning. The phase diffusion caused by the atom-atom interactions in the measurement interferometer do degrade the sensitivity, but for appropriate choice of parameters, an overall increase in sensitivity when compared to a coherent state can still be obtained.



Left: Scheme to enhance the sensitivity of an atom laser interferometer. The first interferometer creates a state with relative phase squeezing via the kerr interaction, and the second interferometer acts as the measurement device. Right: Enhancement in sensitivity as compared to a coherent state.

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Experimental comparison of outcouplers for high flux atom lasers

J.E. Debs, D. Döring, P. A. Altin, C. Figl, J. Dugue, M. Jeppesen, J. T. Schultz,
N. P. Robins, and J.D. Close
Research School of Physics and Engineering, ACQAO, ANU

Atoms interact strongly with their environment, and this sensitivity to, for example, inertial and electro-magnetic forces makes atom interferometers a promising choice for applications as ultra-sensitive detectors of magnetic, optical, and inertial effects. Measurement devices consisting of atom interferometers based around the coherent atomic samples known as Bose-Einstein condensates (BECs) and atom laser beams outcoupled from a BEC are of particular interest due to the possibility of using squeezing to enhance the interferometric sensitivity [1, 2]. In order to fully explore the potential of atom lasers for interferometry, there are stringent requirements on the beam properties, and hence the outcoupler used to achieve this. As with optical interferometry, we desire high flux, low divergence and a simple spatial mode.

In this work, we compare the properties of three differently outcoupled atom laser beams. One outcoupler is based on multi-state radio frequency transitions and two others are based on Raman transitions capable of imparting momentum to the beam.

We have experimentally verified that a two-state Raman outcoupling scheme which imparts momentum to the atoms, results in a larger maximum flux than rf outcoupling or outcoupling from multi-level systems. Coupled with the previous work on divergence and the spatial mode of Raman outcoupled beams [3, 4], it is now clear that a two-level Raman outcoupler produces the highest brightness atom laser beam of any outcoupler to date for magnetically confined samples.

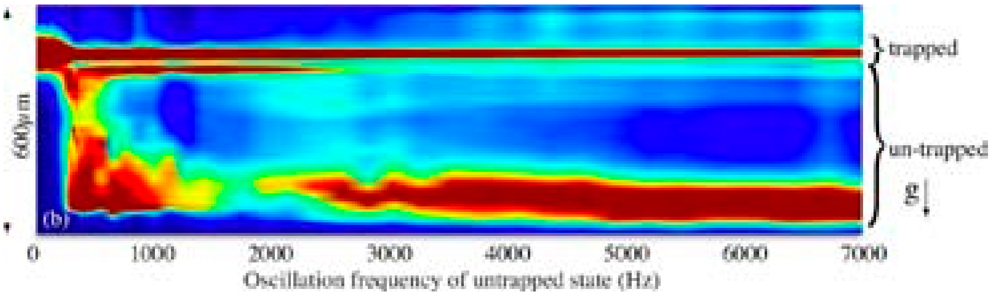

Fig. 1: Absorption image data for a Raman outcoupler operating between Zeeman states of the $F = 1$ ground state of ^{87}Rb. Red (blue) represents a high (low) atom density, and the vertical scale gives the vertical extent in space. These data represent absorption images taken for 14 ms of outcoupling, and different coupling strengths. Each column of pixels corresponds to a single absorption image that has been integrated (summed) in the direction perpendicular to propagation of the atom laser beam. Hence, each column represents the linear atomic density in the vertical direction for a different coupling strength. In the left most columns, a smooth continuous beam is visible for low coupling strengths. As coupling strength is increased, atom laser shutdown can be seen in the form complex density profiles at intermediate coupling strength, and then the clear effect of the dressed states at the highest coupling strengths (right most columns).

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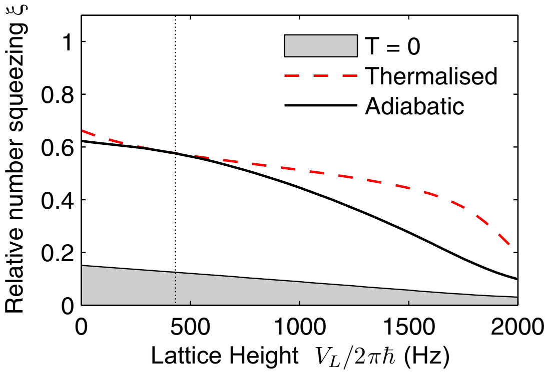
Quantum dynamics and entanglement in Bose-Einstein condensates

M. K. Olsen[1], A. J. Ferris[1], C. M. Caves[2], S. Wüster[2], B. J. Dąbrowska-Wüster[3], and M. J. Davis[1]
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *Department of Physics and Astronomy, University of New Mexico, Albuquerque, USA*
[3] *Max Planck Institute for the Physics of Complex Systems, Dresden, Germany*
[4] *Centre of Theoretical Chemistry and Physics, Massey University, Auckland, New Zealand*

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 quantum noise in the initial conditions means that the technique can incorporate quantum corrections to the classical field dynamics.

1. We have analysed the presence of non-classical correlations in a realistic 3D BEC double-well experiment [2] at finite temperatures using Bogoliubov theory. We have also performed a critical analysis of the procedure of dynamically raising the barrier to drive the system out of thermodynamic equilibrium and found that this can reduce the relative number fluctuations between the two wells [3]. The figure on the right compares the relative number squeezing achievable starting from thermal equilibrium at 11 nK with a 500 Hz barrier height.



2. We have proposed a scheme to generate and measure entangled matter-wave packets via degenerate four-wave mixing of a BEC in a moving 1D optical lattice. In this process atoms from a mother condensate form two entangled daughter condensates with differing momenta. Phase-sensitive homodyne measurements of the atomic fields are necessary in order to prove entanglement between the atomic pulses. We have performed 1D simulations of the scheme including a realistic measurement procedure to demonstrate its experimental feasibility [4].

3. We developed a quantum-metrology protocol to estimate an inter-species scattering length in a Bose-Einstein condensate of N atoms, and showed that using the condensate nonlinearity the measurement uncertainty can decrease faster than $1/N$ without using entanglement [5].

4. Research that was mostly complete in 2008 on the analysis of the formation of multiple 3D bright solitary waves (BSWs) in the collapse of a BEC [6] was published this year. We have found that quantum noise can result in effective repulsive interactions between solitons in one dimension, but not in three dimensions [7].

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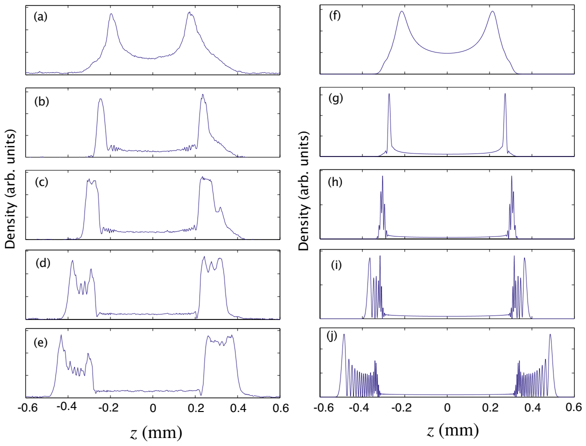
Nonlinear dynamics of Bose-Einstein condensates

S. A. Haine[1], C. J. Foster[1], E. D. van Ooijen[2],
N. R. Heckenberg[2], H. Rubinsztein-Dunlop[2], P. van der Straaten[3], and M. J. Davis[1]
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *School of Mathematics and Physics, UQ*
[3] *Atom Optics and Ultrafast Dynamics, Utrecht University, Utrecht, The Netherlands*

Over the past twelve months there have been two related projects concerning the nonlinear dynamics of Bose-Einstein condensates (BECs) as described by the Gross-Pitaevskii equation (GPE). This mean-field equation is the starting point for understanding many features of dilute gas Bose-Einstein condensates, so it is important to understand its capabilities and limitations.

1. Experiments were peformed in the group of Peter van der Straaten at Utrecht University in the Netherlands to generate shock waves in a large Bose-Einstein condensate in a cigar-shaped trap. They did this by suddenly turning on a blue-detuned laser sheet that intersected the condensate and repelled the atoms from the centre of the cigar. This resulted in density pulses that propagated along the cigar. Due to the condensate nonlinearity the pulses steepen, and as the front edge of the pulse becomes near vertical wave-breaking occurs. Due to the violence of the experiment it is unfeasible to perform a fully 3D GPE simulation of this experiment, even by making use of the cylindrical symmetry of the system. We modelled these experiments using the non-polynomical Schrödinger equation (NPSE) [1].



The NPSE is an effective 1D GPE that takes account of the width of the condensate in the radial direction to make a better model of what is really a 3D system. The simulations showed very good agreement with the density profiles measured in the lab [2]. This is another remarkable achievement for the GPE in a situation where it might otherwise be expected to be invalid. The figure on the right shows experimental density slices in the left column (a–e) and theoretical 1D GPE simulation density profiles in the right column (f–j) following 69 ms of expansion after evolving in the trap for up to 3.0 ms.

2. One of the approximations made in the derivation of the non-polynomial Schrödinger equation is that the radial width of the condensate adiabatically follows the axial density. We have been working at eliminating this approximation, and deriving an equation of motion for the radial width as a function of the axial position coupled to an effective 1D GPE-like equation [3]. This should not only be more accurate than the non-polynomial Schrödinger equation [1], but could also be used to simulate the expansion of a cigar-shaped BEC. This would be useful as BECs are often expanded before they are imaged, and sometimes the relationship between the measurement and the in-trap density is not clear.

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Number Phase Wigner Representation for Efficient Stochastic Simulation

M. R. Hush[1,2], A. R. R. Carvalho[2], and J. J. Hope[1,2]
[1] *Research School of Physics and Engineering, ACQAO, ANU*

Phase-space representations based on coherent states (P, Q, Wigner) have been successful in the creation of stochastic differential equations (SDEs) for the efficient stochastic simulation of high-dimensional quantum systems [1]. By combining the equation of motion produced by these representations with a Fokker-Planck equation, one can produce a set of stochastic differential equations (SDEs) that can greatly reduce the dimensionality of a problem. For example, consider a BEC modelled as a set of N harmonic oscillators. This would typically require a density matrix with D^{2N} components to solve directly (where D is the number of elements you have in your truncated basis). Using a phase space representation one can change this to a set of only N SDEs. This allows quantum simulations on a desktop computer that are otherwise unfeasibly large on any imaginable classical computer.

Unfortunately, the high nonlinearities in a Bose Einstein Condensate (BEC) make it extremely difficult to simulate for long times without making a semiclassical approximation. Long-term simulation of the full dynamics of the quantum field is important for understanding experiments where mean field and perturbative methods fail, such as the dynamics of an atom laser under feedback control. The nonlinearities are the dominant term in the dynamics, and preserve atom number, but they do not preserve a coherent state. We therefore hypothesise that representations based on coherent states are inappropriate for these systems, and that a number-phase based alternative will do better. Historically the investigation of number-phase space methods have been primarily concerned with the visualisation of quantum states and no simple extension can be used to generate SDEs. We presented a novel number-phase Wigner representation that does generate SDEs. We investigated the properties of this new distribution and used it to efficiently produce some potentially useful numerical results.

We examined a single mode problem of a damped anharmonic oscillator, which is analogous to a single-mode BEC. We simulated this system using three different scalable phase space methods: our novel number-phase Wigner representation, coherent truncated Wigner and positive-P. The novel number-phase method required a approximate truncation in some terms, similar to the coherent truncated Wigner method. These solutions were compared to an analytic solution as shown in figure 1. We found the number-phase Wigner representation converged for a longer time than any other competing method and was even able to reconstruct the dampened phase revival of the initial coherent state. These results show this representation has great potential for quantum field simulations where number or phase-conserving terms are dominant, such as BEC. We plan to extend this method to multimode problems, such as the quantum dynamics of a feedback-controlled atom laser.

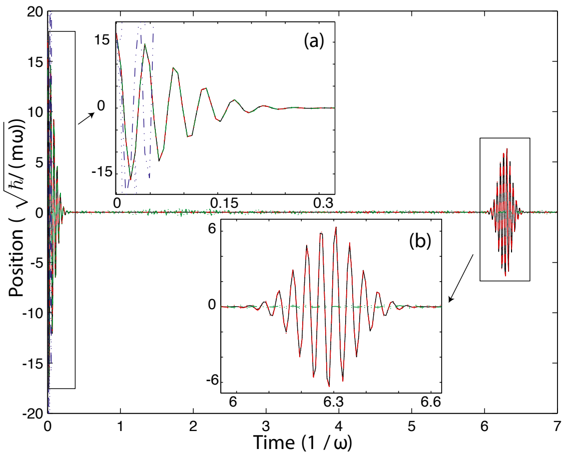

Fig. 1: Position vs. time for a damped anharmonic oscillator integrated using the number-phase Wigner representation (red), truncated Wigner representation (green), gauge-P^+ (blue) and analytic solution (black).

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Extending the realms of numerical stochastic integration

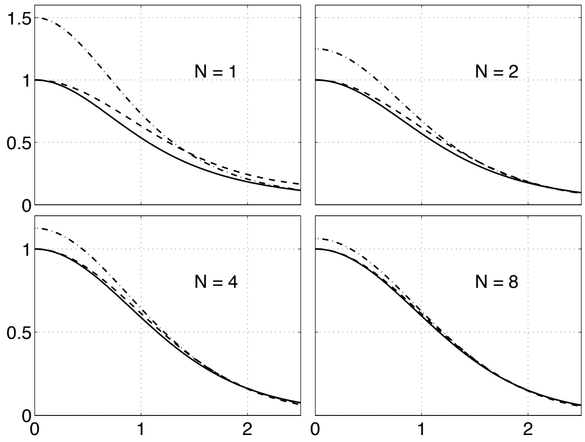
M. K. Olsen
School of Mathematics and Physics, ACQAO, UQ

The numerical integration of stochastic differential equations using phase-space representations is a powerful tool in the investigation of interacting multi-body quantum systems. For quantum optics and quantum atom optics, the representations of choice have been the positive-P and truncated Wigner representations. Both these have well known advantages and disadvantages and we have continued our work to strengthen the former and minimise the latter.

As with all numerical work, initial conditions must be specified. When we wish to investigate quantum dynamics, knowing the quantum state of the fields at the initial time can be crucially important. Traditionally, investigations have often begun with coherent initial states, which may be a good approximation for quantum optical systems, but not for ultra-cold quantum gases. Together with Ashton Bradley (now at the University of Otago), methods to numerically simulate a number of different initial quantum states were developed [1]. Apart from an approximation used to model Fock states in the Wigner representation, necessary because the Wigner function for this state takes on negative values, these were all exact. The Wigner approximation for a Fock state becomes more accurate as the occupation number increases, and is already a good approximation for $N = 10$, below which other methods are more appropriate.

For numerical investigations of ultra-cold atoms, where the interaction terms can dominate, the truncated Wigner representation is often the method of choice. While not exact, it leads to tractable stochastic equations which naturally give symmetrically ordered operator expectation values. This is not a problem until we wish to calculate time-normally ordered quantities such as

$$g^{(1)}(\tau) = \langle \hat{a}^{\dagger}(\tau)\hat{a}(0)\rangle. \tag{1}$$



Two-time correlation functions, $g^{(1)}(\tau)$, for the Kerr oscillator. The solid lines are the exact solutions, the dashed lines are our corrected Wigner solutions and the dash-dotted lines are uncorrected Wigner predictions. The horizontal axis is dimensionless time.

In a collaboration with universities in Ulm, Kaiserslautern and Boston [2], a time-symmetric ordering of the creation and annihilation operators was developed which allows for the calculation of this class of averages. For two-time averages, Kubo's theorem relating the linear response function to two-time commutators is used to calculate the normally-ordered correlation functions. The results have been tested for both the anharmonic (Kerr) oscillator and one dimensional Bose-Hubbard chains with up to ten sites. The method was found to be very accurate and comparatively cheap computationally.
This work can also be combined with recent extensions of the Wigner representation by ACQAO researchers at ANU to add another powerful tool to the arsenal of theoretical quantum atom-optics.

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Non-local spatial pair correlations in a 1D Bose gas

P. Deuar[1], A. G. Sykes[2], D. M. Gangardt[3], M. J. Davis[2],
P. D. Drummond[4], and K. V. Kheruntsyan[2]
[1] *Institute of Physics, Polish Academy of Sciences, Warsaw, Poland*
[2] *School of Mathematics and Physics, ACQAO, UQ*
[3] *School of Physics and Astronomy, University of Birmingham, UK*
[4] *Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT*

The study of two-body and higher-order correlations is an important theme in the physics of ultracold quantum gases. Correlation functions are observables that provide information about quantum many-body wave functions beyond the simple measurement of density profiles. They are of particular importance for the understanding of low dimensional and strongly correlated systems, atomic gases with exotic phases, and systems with multiple order parameters. We have addressed the problem of nonlocal two-particle correlations in a uniform 1D Bose gas with repulsive δ-function interaction. The 1D Bose gas model is one of the simplest paradigms we have of a strongly interacting quantum fluid, owing to its exact integrability [1]. It also holds relevance to an experimentally accessible system, in which the motion of atoms in the gas is confined to the transverse ground-state of a highly anisotropic trapping potential.

We have calculated [2] the spatial second-order correlation function $g^{(2)}(r)$ for the uniform 1D Bose gas in the parameter space characterised by the dimensionless interaction parameter γ and the reduced temperature τ (see Fig. 1). The results span the entire range of physical regimes – from ideal gas ($\gamma \to 0$) to strongly interacting ($\gamma \gg 1$) and from low temperature ($\tau \ll 1$) to high temperature ($\tau \gg 1$) gases. We present the results of perturbative analytic methods available at strong and weak couplings, as well as first-principles numerical results using imaginary time simulations with the gauge-P representation in regimes where perturbative methods are invalid (see Fig. 2). 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.

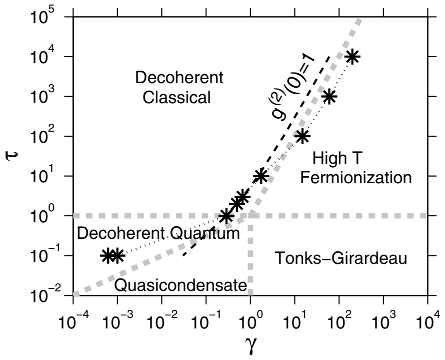

Figure 1. Phase diagram of different regimes in a uniform 1D Bose gas. The asterisks indicate the lowest τ and highest γ accessible using the numerical gauge-P method.

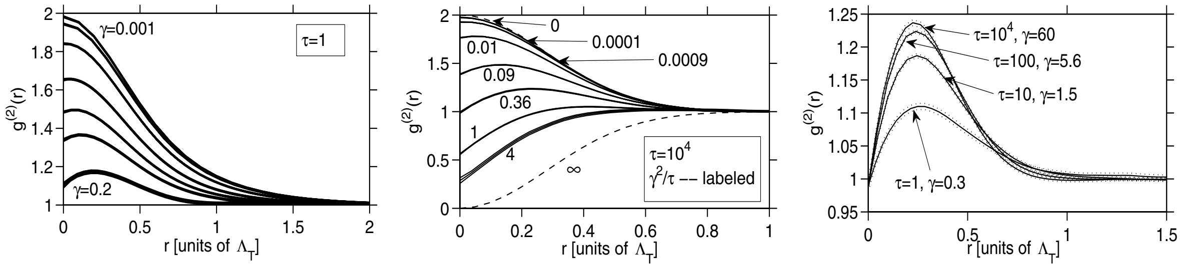

Figure 2. Examples of the pair correlation $g^{(2)}(r)$ as a function of the relative distance r in units of the thermal de Broglie wavelength Λ_T.

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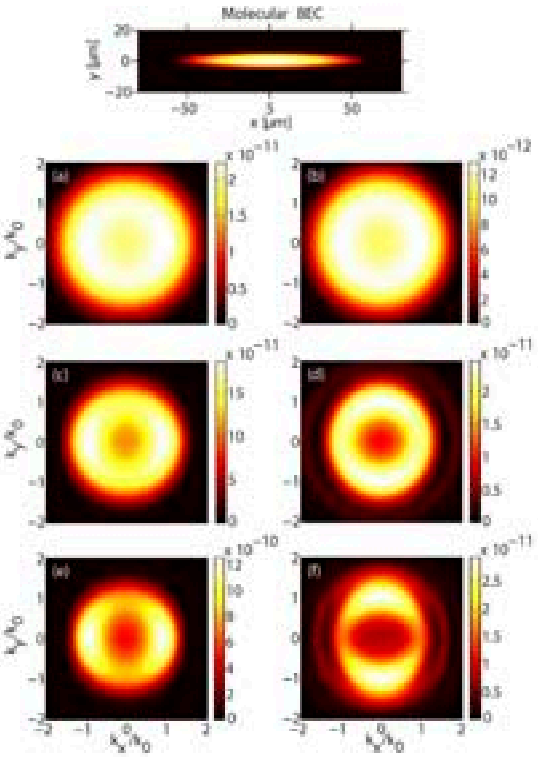
Quantum-atom optics with molecular dissociation

M. Ögren[1], C. M. Savage[2], S. Midgley[1], M. J. Davis[1], M. K. Olsen[1], and K. V. Kheruntsyan[1]
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *Research School of Physics and Engineering, ACQAO, ANU*

The dissociation of a Bose-Einstein condensate (BEC) of molecular dimers into pair-correlated atoms is a process analogous to parametric down-conversion in optics. Down-conversion with photons has been pivotal in the advancement of quantum optics by allowing for the generation of strongly entangled states. In the same way, molecular dissociation has emerged as an avenue for generating strongly entangled ensembles of atoms in the field of quantum-atom optics. This matter-wave analog is of additional interest, however, as it gives rise to the possibility of performing tests of quantum mechanics with mesoscopic or macroscopic numbers of massive particles rather than with massless photons. Also, the molecules in the BEC can be formed by either two bosonic or two fermionic atoms; the latter offers the possibility of a new paradigm of *fermionic* quantum-atom optics.

In Ref. [1] we have modeled the dissociation of two-dimensional, elongated molecular condensates (shown in the top panel of the figure) using the undepleted molecular approximation. For this geometry, the difference in quantum statistics of the constituent atoms (bosons or fermions) manifests as complementary geometric structures in the density profiles of the dissociated atomic clouds. Atomic bosons (with the momentum distributions shown in Figs. (a), (c) and (e) at three successive time instances) are preferentially emitted along the long axis of the molecular BEC, while atomic fermions (Figs. (b), (d) and (f)) are preferentially emitted along the short axis. This anisotropy provides a straightforward way to bin the atomic signal into two opposite bins (left-right for bosons, top-bottom for fermions) and potentially simplifies the measurement of relative atom number squeezing in the opposite bins. In addition to these numerical analysis, we have derived explicit analytic results [2], valid in the short time limit, for the shape and the strength of atom-atom pair correlations (see Annual Report for 2008).



In the regime of strong molecular depletion, we have analysed the relative performance of the Hartree-Fock-Bogoliubov (HFB), the truncated Wigner, and the positive-P methods for dissociation in 1D [3]. An important aspect of our analysis is the inclusion of atom-atom interactions, which can be problematic for the positive-P method. We find that the truncated Wigner method mostly agrees with the positive-P simulations, but can be simulated for significantly longer times. The HFB results diverge from the positive-P and Wigner methods after relatively short times.

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Complete ground state transition rates for the helium 2^3P manifold

S. S. Hodgman, R. G. Dall, K. G. H. Baldwin, and A. G. Truscott
Research School of Physics and Engineering, ACQAO, ANU

Experimental tests of Quantum Electrodynamics (QED) have focused on the precision measurement of key atomic parameters. These include atomic energy level intervals and transition rates, both of which require a complete relativistic treatment of the atom-light field Hamiltonian. High resolution experimental studies of the 2^3P fine structure intervals in helium have shown that differences of several standard deviations exist between experiment and the most recent QED theory.

Until the present work, there has been no comparable study of the transition rates from the 2^3P manifold to the ground state for He. As the fine structure interval studies show, it is important to perform a complete study over the entire manifold in order to test QED predictions. Further, this work completes the series of rare-gas 2^3P_2 lifetimes for Ne, Ar, Kr and Xe.

We present here the final in a series of three separate experiments aimed at determining the transition rates from the metastable helium 2^3S_1 state (He*) and from the 2^3P manifold to the ground state. Each measurement requires a different experimental technique that is optimised to account for the vastly differing transition rates (covering six orders of magnitude) and to benchmark the measured values against a known reference.

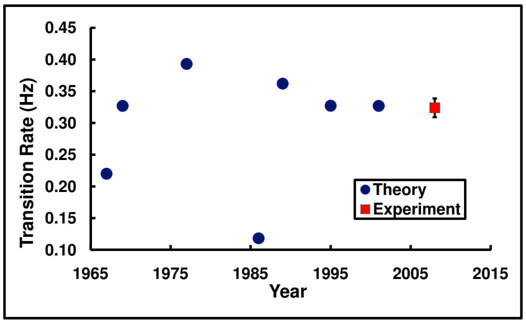

Fig. 1:)(a) Historical progress of theoretical predictions (references shown) for the $2^3P_2 \rightarrow 1^1S_0$ decay rate, along with our experimental determination and associated uncertainty. Estimated uncertainties for the theoretical results are smaller than the data points.

In these latest experiments we measure the rate of photon emission from the 2^3P_2 and 2^3P_0 states to the 1^1S_0 ground state relative to the emission rate from the $2^3P_1 \rightarrow 1^1S_0$ transition, which we have determined previously for the first time. The value for the $2^3P_2 \rightarrow 1^1S_0$ transition is 0.324 ± 0.016 s^{-1}. An upper bound of ~0.01 s^{-1} is placed on the emission rate for the $2^3P_0 \rightarrow 1^1S_0$ transition, which is predicted to be strictly forbidden. Together with our previous measurement of the $2^3P_1 \rightarrow 1^1S_0$ transition rate [1], this work completes the first measurement of the decay rates from the helium 2^3P manifold to the ground state. Along with the measurement of the He* state lifetime [2], we have now determined the decay rates to the ground state for the first four excited triplet states of helium.

All of our experimental measurements are in excellent agreement ($<1\%$) with the most recent QED theoretical predictions [3], providing support for the accuracy of the 2^3P_1 decay rate (4.4%) used to calibrate the other transitions.

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Bose-Einstein condensation of ^{85}Rb

P. A. Altin, N. P. Robins, D. Döring, J. E. Debs, R. Poldy, C. Figl and J. D. Close
Research School of Physics and Engineering, ACQAO, ANU

Recently, we have achieved Bose-Einstein condensation of ^{85}Rb [1], only the second group to do so worldwide [2]. ^{85}Rb has a wide Feshbach resonance at an accessible magnetic field which can be used to change the interaction strength of ^{85}Rb. We are particularly interested in the ability to tune the s-wave scattering length to facilitate the production of a non-interacting or a squeezed atom laser. In our system, a beam of ^{85}Rb and ^{87}Rb atoms is produced in a 2D MOT and is directed through the vacuum system to a 3D MOT in the main chamber. The atoms are pumped into their lower ground states before being loaded into a quadrupole Ioffe-Pritchard type (QUIC) magnetic trap. Here, the ^{87}Rb is selectively evaporated by an rf sweep, sympathetically cooling the ^{85}Rb through thermal contact. Once the temperature of the combined sample has fallen to 20 K, the atoms are transferred to a crossed optical dipole trap and a large magnetic bias field is applied to suppress inelastic collisions in ^{85}Rb. Finally, the depth of the dipole trap is reduced, resulting in further evaporation of both species. With the appropriate magnetic field strength, the ^{85}Rb scattering length can be made positive and a stable condensate of 4×10^4 atoms is created.

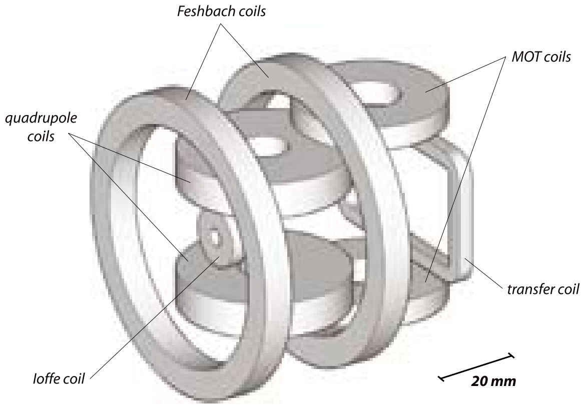

Fig. 1: Magnetic trap coils mounted around the UHV cell.

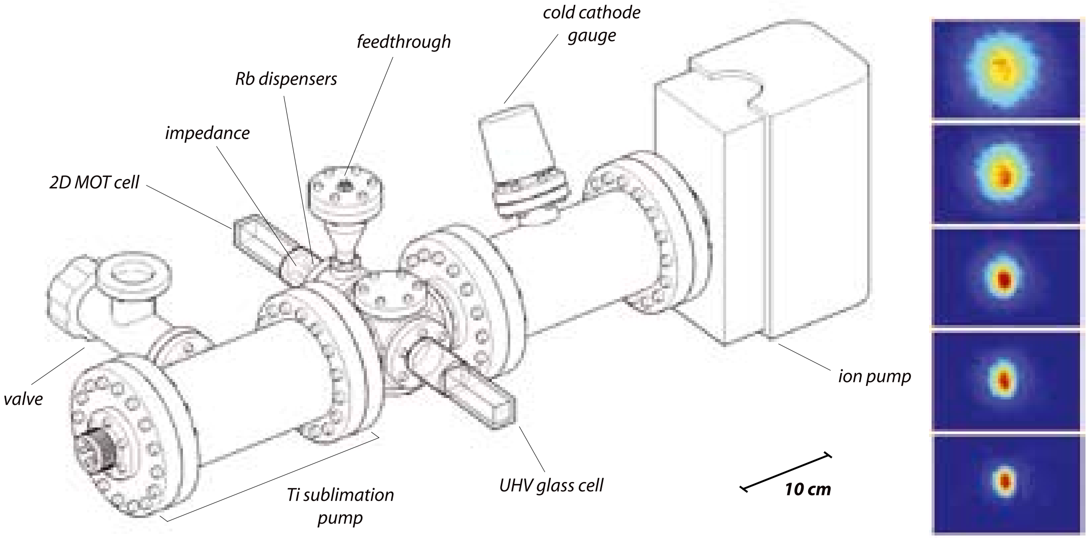

Fig. 2: Vacuum system schematic (left) and absorption images after 20 ms expansion, showing the formation of a ^{85}Rb BEC as the depth of the dipole trap is reduced (right).

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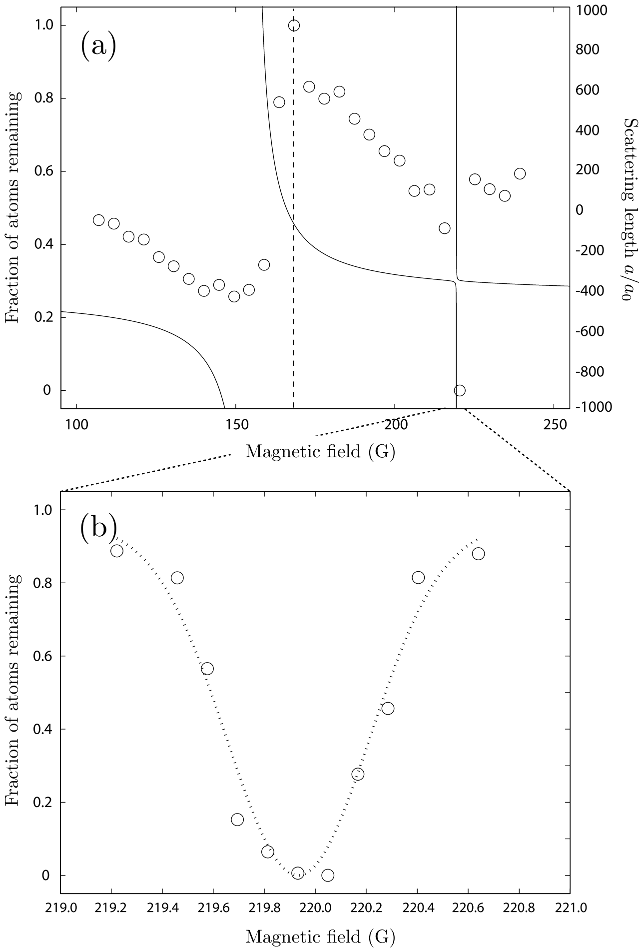
Measurement of inelastic losses in a sample of ultracold ^{85}Rb

P. A. Altin, N. P. Robins, R. Poldy, J. E. Debs, D. Döring, C. Figl and J. D. Close
Research School of Physics and Engineering, ACQAO, ANU

The ability to tune the interparticle interactions in an atomic Bose-Einstein condensate (BEC) has opened up a wide range of new experiments in the field of ultracold atoms. Many experiments have used a Feshbach resonance, a magnetically-tunable molecular bound state, to modify the s-wave scattering properties of ultra-cold atoms. The most notable of these include the Bose-Einstein condensation of cesium [1], the formation of a molecular BEC from a Fermi gas [2], and the demonstration of atom interferometry with a weakly-interacting condensate [3].



We have observed and characterised inelastic loss features in collisions between ultracold ^{85}Rb $|F = 2; m_F = 2\rangle$ atoms [4]. Our apparatus is described elsewhere in this annual report. The graphs on the left show the fraction of ^{85} atoms remaining in the dipole trap after 10 s as a function of the applied bias field. Loss from the dipole trap is enhanced on the low field side of the Feshbach resonance and peaks as the elastic scattering length diverges at 155 G. The inelastic loss is minimised at around 168 G, where the scattering length vanishes. The loss at 219.9(1) G with a width of 0.28(6) G, which we associate with a narrow Feshbach resonance predicted by theory [5], was previously unobserved. The lower figure on the right shows a more detailed measurement of the feature. The loss at this field is significantly greater than at the broader Feshbach resonance, even though the two-body loss coefficient is predicted to be two orders of magnitude lower here than at 155G [6], implying a particularly high three-body loss rate.

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Suppression of Penning ionisation in a spin polarised mixture of Rubidium and He*

L. J. Byron, R. G. Dall, W. Rugway, A. G. Truscott
Research School of Physics and Engineering, ACQAO, ANU

Ultracold mixtures of atoms have been widely studied, due to their interesting collisional properties as well as their appropriateness for sympathetic cooling e.g. of fermions. However, there has only been one previous investigation of a cold alkali-noble gas mixture in which metastable argon (Ar*) atoms were simultaneously trapped with Rb atoms. This study was conducted in a magneto-optic trap (MOT) where the atoms are essentially unpolarised and an unpolarised Penning rate was measured. The additional step of determining the polarised rate by implementing magnetic trapping was not pursued, presumably because the production of an Ar* BEC is not feasible due to the large inelastic loss rates still present in spin polarised Ar* [1].

Here we present the results of experiments in which we probe the Penning ionisation rates of a mixture of ultracold He*-^{87}Rb atoms. We are able to demonstrate that a high degree of suppression exists for the polarised case and put an upper limit on the polarised Penning rate constant at 5×10^{-12} cm^3/s. Such a low rate constant might make possible a dual He*-^{87}Rb BEC, which would be an interesting environment to create exotic He*-^{87}Rb molecules in a similiar manner that long range He* dimers have been previously demonstrated.

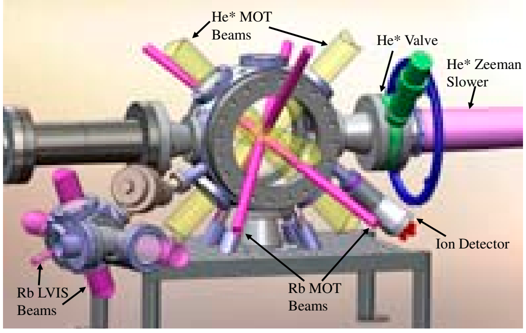

Fig. 1: Experimental setup used to produce dual He*-^{87}Rb MOTs. He* MOT beams are shown as transparent (yellow) beams while the solid (pink) beams represent the ^{87}Rb laser beams.

Suppression of Penning ions should occur in the case of a spin polarised mixture. We probe this suppression by loading both clouds of atoms into a magnetic trap. In such case both the He* and ^{87}Rb atoms are spin polarised (He* in the m_j =+1, and ^{87}Rb in the m_f = +2). Within the noise levels of our experiment we observe no increase in ion production due to the presence of ^{87}Rb in the spin polarised mixture. While this means we can not determine a spin polarised Penning rate coefficient for the mixture it allows an upper limit to be determined. We determine the limit to the rate constant to be 5×10^{-12} cm^3/s, demonstrating a spin polarised suppression of at least a factor of $\sim$ 100.

This surprising result can be explained by the fact that in our mixture both species are in symmetric S states, while all other trappable noble gas atoms are in asymmetric metastable P states. In the case of a collision involving two metastable atoms both in a P state the atoms experience a mutual electrostatic interaction. In the case of metastable neon the asymmetric P-core generates an electric quadrupole-quadrupole potential which depolarises the atoms during their approach and thus Penning ionization is no longer forbidden by spin conservation. For a He*-^{87}Rb mixture the interaction of ground state atoms is purely Van der Waals and thus spin polarisation can lead to a large suppression of Penning ions.

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Single Atom Detection Using a High-Finesse Optical Cavity

R. Poldy, B. C. Buchler, P. Altin, N. Robins, J. D. Close
Research School of Physics and Engineering, ACQAO, ANU

We aim to build a single-atom detector for cold neutral atoms, that will be an important component of atom optics experiments, in analogy to single-photon detectors used in quantum optics. Detection is achieved via observations of an atom's interaction with light, and several research groups have made use of high finesse cavities to increase the interaction strength, and detect single atoms. Observations of changes in a probe beam in the detection cavity (DC) indicate the presence of a single atom. In modelling work in the earlier stages of this project we determined the optimal cavity design and operating regimes for high quantum efficiency detection [1].

Our current focus is the experimental implementation of the detection apparatus. We have built and characterised our DC. Significantly, the finesse is ~ 12000, which is moderate in comparison to the cavities used in cavity QED experiments that often have finesses in excess of 100000, making our mirror coatings easier and cheaper to manufacture. Our mirrors were custom machined and coated, and we assembled the components in a clean-room in-house [Fig 1.(a)].

The DC needs to have a stable resonant frequency with respect to the atomic transition and probe laser. In order to independently adjust the cavity and laser frequencies, we make use of a far-detuned stabilisation laser to lock the DC to an absolute frequency reference. Both probe and stabilisation lasers need to be frequency stabilised. We make use of the Pound-Drever Hall locking technique for all our locks, and employ the following novel locking scheme [Fig. 1(b)]:

The 780 nm probe is stabilised to a D2 line of ^{87}Rb. This absolute frequency is transferred to the 840 nm stabilisation laser via a transfer cavity (TC). The DC length is tuned to transmit the probe laser, and the stabilisation frequency is then tuned so that it, too, is resonant in the DC. Since both lasers need to be resonant in the DC and the TC simultaneously, we must be able to tune one of the lasers independently in *both* cavities. To achieve this, we add strong side bands to the 840 nm laser, using a fibre-coupled electro-optic modulator (EOM) and use the laser current control to shift carrier and side bands together until one of the sidebands is resonant with the DC. It is this frequency on the stabilisation laser to which the DC is locked. We then tune the relative frequency between the stabilisation side bands and carrier using the EOM controller, so that the carrier frequency is resonant in the TC, and lock the laser to that cavity using this frequency.

The next step is to use a 2D magneto-optical trap as an atomic source, and to characterise the flux of atoms from this source, using single atom detection.

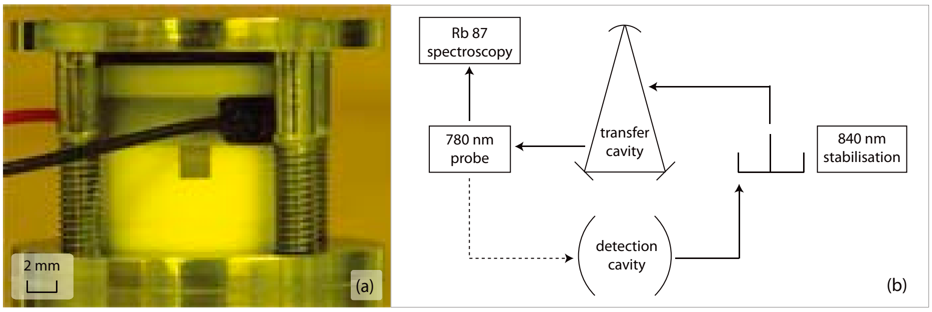

Fig. 1(a) The assembled detection cavity. (b) Frequency locking scheme.

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Probing Zeeman coherence with four-wave mixing

A. M. Akulshin, A. I. Sidorov, R. J. McLean, and P. Hannaford
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

Potential applications in optical communication and quantum information processing as well as fundamental aspects of atom-light interactions are generating widespread interest in coherent atomic media. To effectively control the properties of such media the spectral and temporal nonlinear processes occurring in them must be understood, since light-induced long-lived coherence significantly enhances the nonlinear susceptibility in the vicinity of the Raman transition. Our investigation of nearly degenerate wave mixing in Rb vapours with coherence between Zeeman states illustrates the rich potential this approach offers for understanding the processes involved in generating the atomic nonlinearities that enhance the four-wave mixing.

Two acousto-optic modulators are used to produce mutually coherent drive and probe beams with a small tunable frequency offset δ from an extended-cavity diode laser. We use homodyne and heterodyne methods to separate the frequencies of the co-propagating drive and probe laser fields and components resulting from the four-wave mixing (FWM) processes. In both methods, the signal from a photodiode monitoring the transmitted fields is sent to a radio frequency spectrum analyzer.

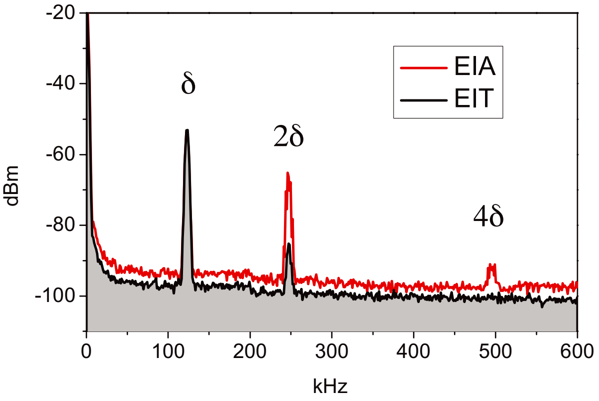

Fig. 1: Four-wave mixing spectra obtained for drive and probe fields separated by $\delta \simeq$125 kHz.

Fig. 1 shows FWM spectra in Rb vapour taken under conditions of electromagnetically induced transparency (EIT) [1] and electromagnetically induced absorption (EIA) [2] using the homodyne detection method. Beating of the drive and probe fields generates a strong signal at δ and occurs even for off-resonant radiation, while the signal at 2δ requires FWM to have occurred. The 2δ signal can arise, for example, as a result of the new wave at $2\nu_D - \nu_P$ beating with the probe wave at ν_P.

The spectra demonstrate that the four-wave mixing is more efficient in the EIA medium under otherwise similar experimental conditions. This observation is consistent with the values of the Kerr coefficients measured directly in both cases, where higher values are found in EIA media.

We have shown that two mutually coherent, co-propagating waves with a small detuning δ may produce up to ten new mutually coherent co-propagating optical waves in Rb vapour. Our study could extend the physical basis of the efficient control of wave mixing in coherently driven atomic media [3].

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Theory of two-component BEC interferometry

B. J. Dalton
Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT

Many previous treatments [1, 2] for two component BEC interferometry are based on the simplest assumption, namely that during the interferometric process the condensate is unfragmented, with all bosons occupying the same single particle state. The latter is a linear superposition of the two internal states. Equations for the spatial wave functions associated with these internal states have been obtained in the form of coupled Gross-Pitaevskii equations. However, there are two distinct single particle states each boson could occupy, and for N bosons the $N+1$ dimensional state space for such two mode theories - such as the present theory and similar work in [3, 4] - allow for more general quantum states than just those that are unfragmented. Two mode theories have previously been developed for single component BECs with two orthogonal spatial modes (such as in double-well interferometry) [5, 6, 7], and fragmentation effects shown in [7].

The quantum state of the N boson system is written as a superposition of the Fock states with amplitudes $b_k(t)$. Each Fock state is a fragmented state, with definite numbers $\frac{N}{2} \mp k$ of bosons respectively in the two modes $\phi_F(\mathbf{r},t)\,|\,F\rangle$ and $\phi_G(\mathbf{r},t)\,|\,G\rangle$ (where the internal states are $|F\rangle$, $|G\rangle$ and the spatial mode functions are $\phi_F(\mathbf{r},t)$, $\phi_G(\mathbf{r},t)$). The Dirac-Frenkel variational principle can be used to obtain matrix mechanics equations for the amplitudes $(k = -N/2, .., N/2)$

$$i\hbar\frac{\partial b_k}{\partial t} = \sum_l (H_{kl} - \hbar U_{kl}) b_l$$

and generalized Gross-Pitaevskii equations for the mode functions $(a = F, G)$

$$X_{aa}\, i\hbar\frac{\partial}{\partial t}\phi_a = X_{aa}(-\frac{\hbar^2}{2m}\nabla^2 + V_a)\,\phi_a + \sum_{b\neq a} X_{ab}\,\Lambda_{ab}\,\phi_b + \sum_b (g_{ab} Y_{ab\,ba}\,\phi_b^*\,\phi_b)\,\phi_a.$$

The $N+1$ amplitude equations describe the system evolution amongst the possible Fock states. The Fock state Hamiltonian and rotation matrix elements H_{kl}, U_{kl} depend on the mode functions $\phi_a(\mathbf{r},t)$. The two coupled Gross-Pitaevskii equations are non-linear in the mode functions. The one and two body correlation functions X_{ab} and $Y_{ab\,ba}$ depend quadratically on the amplitudes $b_k(t)$, and reflect the relative importance of the different Fock states during the interference process. The trap potential is V_a, the inter-component coupling term is Λ_{ab} and collisions are described by the g_{ab}.

The present self-consistent amplitude and mode equations are more general than expressions in [1,2], and differ from those in [3,4]. They can be used to treat various BEC interferometry experiments, such as Ramsey interferometry. Collisions may be ignored during the short coupling pulses, where the evolution is shown to be equivalent to rotations of the Bloch vector. During the non coupling evolution, the magnitudes $|b_k(t)|$ of the amplitudes remain constant, but there is evolution of the phase factors $A_k(t)$, where $b_k(t) = |b_k(t)|\exp(-iA_k(t)/\hbar)$. Fragmentation effects would imply that the Bloch vector no longer remains on the Bloch sphere.

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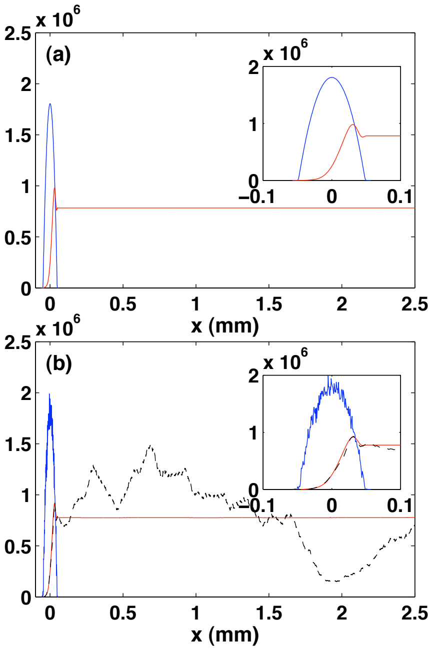
C-field simulations of thermal Bose-Einstein condensates

G. M. Lee[1], S. A. Haine[1], M. C. Garrett[1], C. J. Foster[1], A. S. Bradley[2],
R. N. Bisset[2], P. B. Blakie[2], C. Ticknor[3], T. Simula[4], and M. J. Davis[1]
[1] *School of Mathematics and Physics, ACQAO, UQ*
[2] *Jack Dodd Centre for Quantum Technologies, University of Otago, Dunedin, New Zealand*
[3] *Centre for Atom Optics and Ultrafast Spectroscopy, ACQAO, SUT*
[4] *Department of Physics, Okayama University, Okayama, Japan*

The aim of this project is to continue to develop and apply methods for describing the dynamics of Bose-Einstein condensates (BECs) at finite temperature. The techniques being utilised are approximate; however they are aimed at performing non-perturbative calculations for realistic experimental systems [1].

1. The project on developing a 1D model of a continuously pumped atom laser using a stochastic Gross-Pitaevskii equation is nearing completion. 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 by Raman outcoupling. We have focused 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 [2]. The figure shows a comparison of an atom laser at zero temperature (upper panel) and finite temperature (lower panel). The solid blue curves show the instantaneous condensate density, and the dashed black curves the instantaneous atom laser beam density. The red solid curves are the time averaged beam densities.

2. We have modelled experiments by the University of Queensland BEC group on the formation of condensates by combining a 1D laser sheet with a cigar-shaped BEC. The laser sheet can either be applied adiabatically (in which case entropy is conserved) or suddenly (following which the energy is conserved). We have calculated the expected final condensate fraction and temperature using Hartree-Fock theory, and found good agreement with the data. In the past twelve months we have modelled the condensate formation dynamics using quantum kinetic theory and are currently trying to understand the discrepancies with the experimental data.



3. Ongoing work on the pairing properties of vortices in two-dimensional homogeneous Bose gases was submitted for publication [3]. Other work on the properties of the Berezinskii-Kosterlitz-Thouless phase of the trapped 2D Bose gas was published in 2009 [4].

4. The numerical technique we have developed over the past several years for solving the projected Gross-Pitaevskii equation using an efficient harmonic oscillator representation was extended to incorporate dipolar interactions between the particles [5]. It was also extended and parallelised to be able to simulate spinor (multi-component) Bose systems.

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Stability and dynamics of spinor Bose-Einstein condensates

M. Matuszewski, T. J. Alexander, and Yu. S. Kivshar
Research School of Physics and Engineering, ACQAO, ANU

The spin degree of freedom of spinor Bose-Einstein condensates (SBECs) leads to a wealth of new phenomena not possessed by single-component "spin-frozen" condensates. The quest to understand the properties of these multi-component matter waves has attracted theorists and experimentalists alike, however there are still fundamental questions to be answered. We have sought to answer three of these key questions: what are the properties of an SBEC in a weak homogeneous magnetic field? What is the relationship between excitations and the speed of sound in a SBEC? How does the spin degree of freedom affect matter wave dynamics in a double well? The results in each of these areas are described in turn.

1. **Excited spin states and phase separation in spinor Bose-Einstein condensates** [1]. We have shown recently that a homogeneous antiferromagnetic SBEC in the presence of a weak homogeneous magnetic field may be unstable and develop spin domains in evolution [2] however this prompted the question, what is the ground state in this case? We have found that in the presence of a weak magnetic field the ground state of an antiferromagentic condensate displays spin domains, with the relative extent and spin populations fixed by the magnetization of the condensate and the strength of the magnetic field. In the presence of a spatially varying magnetic field (such as a harmonic trap) these spin domains persist, with the $m_f = 0$ spin component occupying the centre of the trap (see Fig. 1). These results open up the possibility of the experimental observation of spin domain formation in trapped antiferromagnetic condensates.

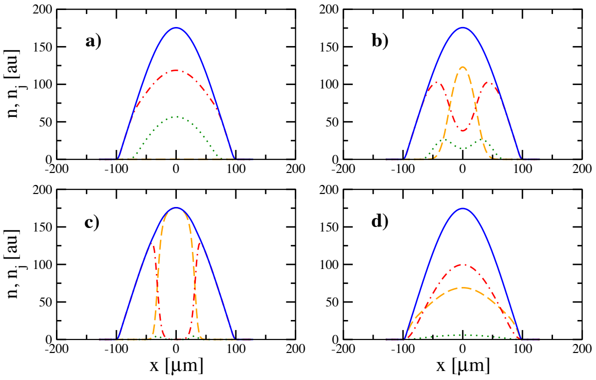

Fig. 1: Ground state profiles in a harmonic trap potential. Phase separation occurs in the polar ^{23}Na condensate when the magnetic field strength is increased from (a) $B = 0.1$ G to (b) $B = 0.12$ G and (c) $B = 0.25$ G. For comparison, the ground state of a ^{87}Rb condensate is shown in (d) for $B = 0.2$ G. The $m_f = +1, 0, -1$ components are depicted by dash-dotted, dashed, and dotted lines, respectively. The solid lines show the total density.

2. **Spinor Bose-Einstein condensate flow past an obstacle** [3]. We examined the problem of a defect moving through a SBEC above and below the speed of sound. We found that there are two speeds of sound in a three-component SBEC, however only one of these appears to be important. We found that exceeding this speed of sound dark or vortex solitons are generated. The effect of the second speed of sound is still an open question.

3. **Spinor Bose-Einstein condensates in double-well potentials** [4]. We characterised completely the possible stationary solutions and their stability for an SBEC in a double well potential. We discovered new asymmetric double-well states and demonstrated the existence of periodic spin oscillations, all made possible by the parametric spin interaction.

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Bunching of a pulsed atomic source

A. G. Manning, S. S. Hodgman, R. G. Dall, and A. G. Truscott
Research School of Physics and Engineering, ACQAO, ANU

An interesting phenomenon involving the quantum statistics of fermions and bosons is the Hanbury Brown-Twiss [1] effect, where interferometric experiments can be performed with the intensity of particles (either in the density of atoms, or $|E(r,t)|^2$ in a classical model for light). The Hanbury Brown-Twiss effect is a second order coherence effect, in contrast with a first order coherence in amplitude such as that measured by a Michelson interferometer. Physically, this amounts to determining the probability of measuring a particle at a position or time, given that other particles exist nearby. Thermal bosons are expected to arrive in bunches, thermal fermions antibunch to avoid one another, and a coherent BEC is uncorrelated (Poissonian).

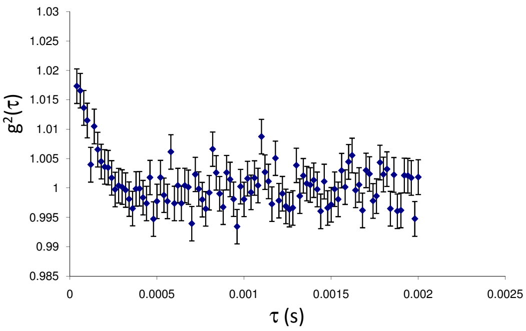

Fig. 1: Second order correlation function for the arrival times of atoms from a thermal source. For earlier times (i.e. times within the coherence time of the source) we observe an increase in the probability that two particles will be detected. This so-called bunching is the result of the famous Hanbury Brown-Twiss effect.

In our experiments, we release thermal atoms from the magnetic trap by applying high power RF pulses which output-couple atoms into untrapped states. The pulses are very short in time and thus have a large frequency spread, resulting in an outcoupled cloud which is an image of the original, only about 30 times lower in atom number. The experiment implements a recently installed delay-line system, which allows the position and time of a detection event to be measured. The delay-line consists of two layers of wire which are wound around a rectangular base, where a signal from each of the two ends of the two wires can be measured. In addition to a signal for the time of arrival, the position of a particle striking the detector can be ascertained from the time taken for the signal to propagate to both ends of the two layers of wires.

We use the pulsing technique since simply dropping the entire cloud on the detector would lead to saturation effects. As a result we can collect large amounts of data from a single run of the experiment and exploit this method to investigate the quantum statistics of a pulsed thermal atomic source.

We observe bunching on short time scales for the pulsed thermal source, as shown in the figure above, while for a pulsed atom laser no bunching is observed (not shown). Performing this experiment is the first of many steps the ANU metastable helium BEC group will be taking to probe further into correlation and entanglement effects in ensembles of atoms. In particular, we aim to investigate the Einstein-Podolsky-Rosen paradox, which challenges the idea of local reality in quantum mechanics, for the first time with massive particles.

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Coherent 455 nm beam production in a cesium vapor

J. T. Schultz[1], S. Abend[1,2], D. Döring[1], J. E. Debs[1], P. A. Altin[1], J. D. White[3],
N. P. Robins[1], and J. D. Close[1]
[1] *Research School of Physics and Engineering, ACQAO, ANU*
[2] *Leibniz Universität Hannover, Germany*
[3] *Department of Physics, Juniata College, Huntingdon, USA*

The effects of atomic coherence and interference have become useful and important tools in optical physics, particularly for the enhancement of nonlinear interactions between atoms and light. The atomic species rubidium and cesium have been studied for their apparent suitability for frequency upconversion and specifically the generation of shortwavelength laser beams [1, 2].

We demonstrate efficient frequency upconversion in a resonant atomic media with low-power, cw lasers via techniques of interference and atomic coherence [3]. Two 30 mW infrared lasers induce strong double excitation in a heated cesium vapor cell, allowing the atoms to undergo a double cascade and produce a coherent, collimated, blue beam copropagating with the two pump lasers (see Fig. 1).

The 455 nm beam is found to be collimated with a divergence less than 0.1 mrad. An interference pattern from a MachZehnder interferometer with unequal path lengths confirms that the beam has substantial spatial and temporal coherence with a fringe visibility of 93%. The greatest efficiency is obtained when both pump beams are circularly polarized thereby utilizing cycling transitions at each excitation stage. Unlike a similar system in rubidium [4], no blue-beam production is observed for large detunings of the pump beams. It is possible that this method for frequency upconversion can be extended to other elements, such as sodium and lithium, in order to produce a coherent beam of UV radiation (330 nm and 323 nm, respectively).

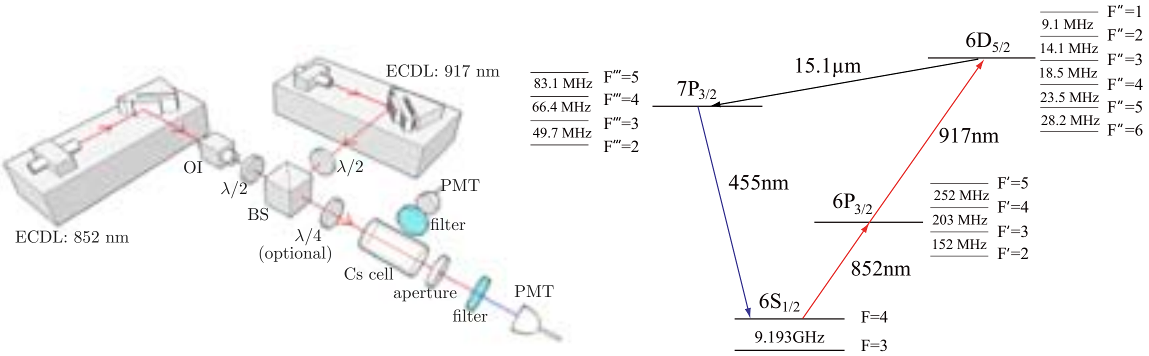

Fig. 1: Experimental setup (Left). Two infrared lasers copropagate through a ^{133}Cs vapour cell thus producing 455 nm radiation. The blue beam is sent through an aperture and a bandpass filter and is detected with a photomultiplier tube (PMT). A PMT is also used to measure the blue fluorescence in the cell. OI, optical isolator; BS, nonpolarizing beam splitter. Energy level scheme in ^{133}Cs (Right). The atoms undergo a double cascade through the $^7P_{3/2}$ state, producing a 455 nm beam on the transition to the ground state.

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** High impact article

ACQAO Success as a Centre of Excellence

This Centre of Excellence was created by a distinguished group of individual researchers who have used the opportunities given by stable long term funding to create new outstanding results. From the beginning our Centre had three major missions: (i) to develop new tools for the development of future quantum technologies, (ii) to create a truly collaborative Centre which combines the best researchers in the country and links them with the leading groups in the world and (iii) to enhance the research environment in our field. We have succeeded in all these categories:

ACQAO has achieved all the original research goals that are reported in our publications and summarised in the list of research highlights (pages 5–15). Our work has high impact as can be seen by the impressive number of citations (see page 64, KPMs). In addition, we have achieved many of our new goals set in 2007 for the second phase of our Centre. Again all projects made significant advances as reported in the science pages (pages 18–53).

ACQAO has provided a creative environment where researchers can focus on research, and have exemplary laboratories and offices. These factors have created greater opportunities to meet other excellent researchers within the Centre and throughout the world. The Centre provides PhD training of the highest calibre and has supported many outstanding young scientists who are now contributing to the research field across the world. There have been many success stories of young scientists advancing into new careers; some of these include the following:

Staff

Chris Vale appointed as new long-term staff member at SUT

Ping Koy Lam appointed as Professor and ARC Future Fellow at ANU

John Close and Ken Baldwin appointed Professors at ANU

Nick Robins (ANU) and Hui Hu (SUT) appointed ARC QEII Fellowships

Grainne Duffy became research fellow at ENS Paris and is now project leader with NanoV (www.nanov.com).

Joe Hope appointed to a continuing position as Reader at ANU

Joel Corney appointed as Senior lecturer and Matt Davis as Associate Professor at UQ

Students

Warwick Bowen (2003 ANU PhD), AIP Bragg Medal, currently Lecturer at UQ

Piotr Deuar (2004 UQ PhD), Marie-Curie Fellowship at Universite Paris-Suc XI

Simon Haine (2006 ANU PhD), APD at UQ

Vincent Delaubert (2006 ANU Cotutelle PhD), Lecturer Grandes Ecoles Preparation school in Paris

Shannon Whitlock (2007 SUT PhD), Amsterdam with a Marie-Currie Fellowship.

Magnus Hsu (2007 ANU PhD), Postdoc Stanford then UQ in 2009, currently at NMI

Gabriel Hetet (2008 ANU PhD), Postdoc at Insbruick

Julien Dugue (2009 ANU Cotutelle PhD), Lecturer Grandes Ecoles Preparation school in Paris

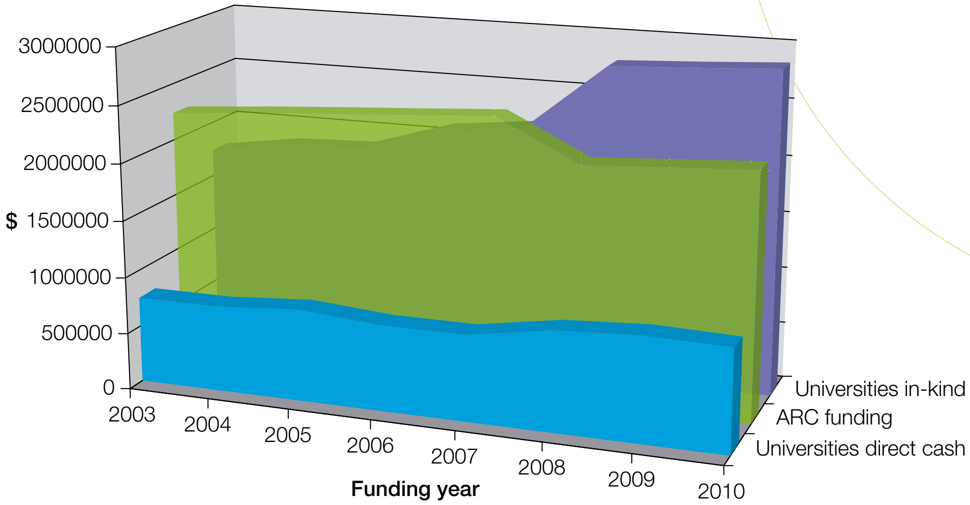
Mandip Singh (2008 SUT PhD), Postdoc with University of Vienna

G. Veeravalli (2009 SUT PhD), Postdoc at Heidelberg

Through the development of its people ACQAO has demonstrated that the concept of a centrally funded and managed Centre of Excellence (CoE) is a very successful way to create and enhance science at the highest international level. We have shown that the quality of the research achieved in a CoE is far higher than typically can be achieved through multiple groups of independent research grants. The evidence lies in the international impact we have created as shown in our KPM's, page 64.

ACQAO developed the topic of quantum-atom optics as major strategic areas in our host universities. Throughout the life of our Centre the support

Figure 1: ACQAO 2003–2010 Universities in-kind and cash and ARC funding



by the host universities has increased, new staff positions have been created and we received several additional equipment grants. The universities value our research, see the importance of our work, and reward the teams for their success. We are seen as role models for excellence in research and in effective research management. Each university partner has given continuous financial support and increased their in-kind funding throughout the life of the Centre; Figure 1 demonstrates this evidence over the years.

International collaborations and linkage

The model of long distance collaboration created by ACQAO has gained much interest from other countries and has been quoted as exemplary in several other successful applications, which have formed new clusters of Excellence. In particular, the Institut Francilien de Recherche sur les atomes froids (IFRAF) in France and the German Excellence cluster for Quantum Engineering and Space-Time Research (QUEST) in Germany have followed our example.

ACQAO staff and students visiting our European partners following Les Houches workshop, February 2009

We have established intensive research links and student networks with these two Centres in Europe and held six successful student workshops between the three Centres with the next meeting in July 2010. We have attracted the leading conferences in our field to Australia, ICOLS in 2003 and ICAP in 2010. There is an ever growing interest from young scientists across many countries to join our research team, presently 13 international students and 7 postdocs who have chosen our Centre, including two Alexander von Humboldt Fedor Lynen Fellows.

Over the years we have strengthened our scientific links with the international research community, in particular in Europe. We have intensified the scientific exchange with our official partners in Hannover, Erlangen, Amsterdam, Paris, London, Dunedin and Auckland, and our new partner Innsbruck. They all received visits from ACQAO staff and some hosted visits of students. Particularly strong links exist with the following international partners.

1. Laboratoire Kastler Brossel (LKB) in Paris, France, on quantum imaging and atom lasers has three cotutelle (joint PhD projects) with the ANU, V.Delaubert, J.Dugue and J-F.Morizur, supervised by M.Leduc, C.Fabre and N.Treps (LKB) with J.Close, N.Robins and H.-A.Bachor. At the same time, E.Giacobino (LKB) developed with P.Drummond, M.Reid & Q.He a novel theory of dynamical quantum memories. M.Jeppesen, N.Robins and J.Close worked with D.Guery-Odelin (LKB) on atom lasers.

2. IFRAF in Paris and Laboratoire Charles Fabry, Palaiseau, on atomic four wave mixing in BECs, involving C.Westbrook and A.Aspect with K.Kheruntsyan.

3. University of Arizona, Tuscon, USA on spontaneous vortices in BECs; involving B.P.Andersen and C.N.Weiler with A.Bradley and M.Davis

4. Amherst College, USA on two component BECs, R. Anderson (SUT) spent three months on collaborations with D.Hall.

5. Innsbruck University and Austrian Academy of Sciences, on Bragg scattering from a 2D Fermi gas; M. Mark and R. Grimm obtained an ARC Linkage International grant to work with C.Vale and P.Hannaford.

6. Toronto University, on developing a hydrodynamic theory of Fermi gases; A.Griffin with X.Liu.

7. QUEST in Hannover, on Feshbach resonances and developments of atom lasers (J.Arlt, S.Abend, O.Topic with N.Robins, J.Close, J.Debs) and the optimisation of squeezing (R.Schnabel, B.Hage with P.K.Lam and H.A.Bachor).

8. Max Planck Institute, Erlangen, on the analysis of squeezing in optical fibres and optical entanglement (G.Leuchs, O.Glöckl with J.Corney & P.Drummond) and the design of tunable squeezers (with B.Buchler and P.K.Lam).

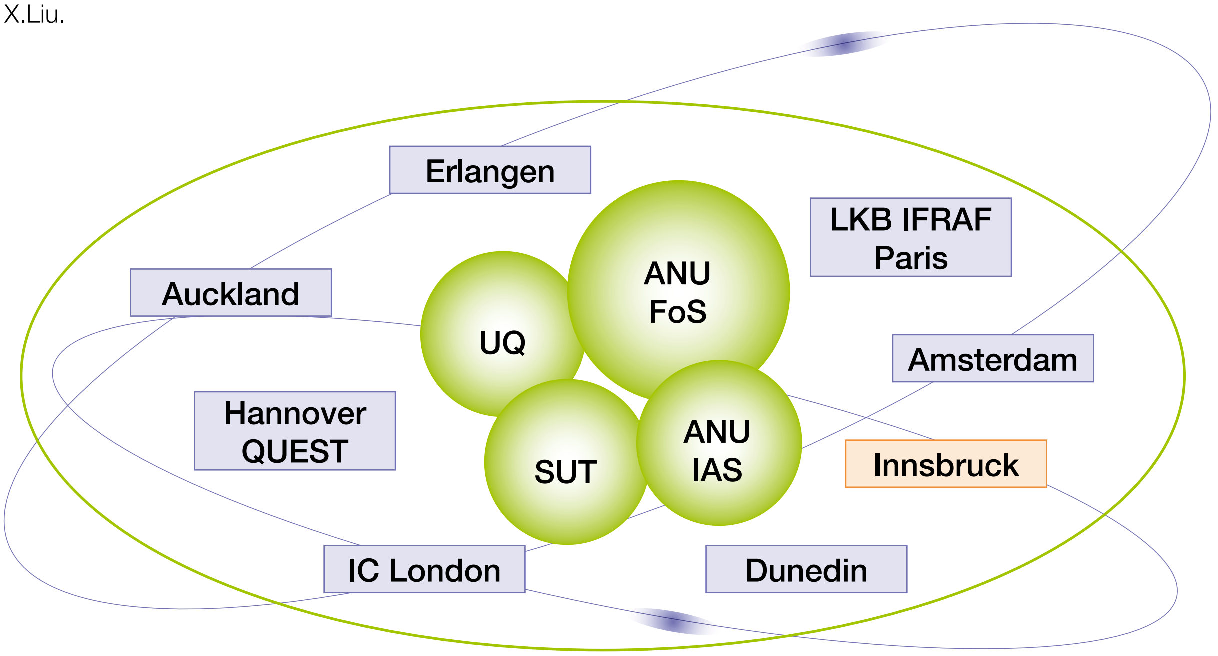
9. Danish Technical University, on the development of spatial squeezing (M.Lassen, P.Buchave with J.Janousek and H.-A.Bachor) including three special lecture courses at DTU.

10. Otago University, Dunedin, where we have several joint projects (B.Blakie, K.Longdell, W.Bowen with M.Davis, G.Hetet and B.Buchler).

11. Renmin University of China, on the theory of strongly interacting Fermi gases (H.Hu with P.Drummond & X.Liu)

12. Stanford University, on atom interferometers (M.Kasevich with J.Close & D.Döring)

13. University of Trento, on the theory of second sound in strongly interacting Fermi gas (H.Hu, X.Liu, P.Drummond, S.Stringari, L.Pitaeuslei, E.Taylor)



Official links and exchanges between the Centre and the international partners

Together with QUEST and IFRAF we held a most successful series of seven workshops for young researchers and students. This has created the basis of an extremely useful international research network and provides our young researchers access to the European research community. It allows them to showcase their Australian work as well as attracting talented researchers to Australia.

The latest workshop was held in February 2009 in Les Houches, France with 15 attendees from ACQAO. This was linked with a QUEST symposium in Hannover. ACQAO students and staff also used this opportunity to visit many research groups across Europe.

The next step in this series will be the International Conference on Atomic Physics (ICAP 2010), organised by members of ACQAO in Cairns July 2010. This will be happening in conjunction with a special international student workshop. Being selected to organise ICAP, which is the leading conference in our field, is a distinction in itself and underlines the high ranking our work in Australia has achieved.

Laboratories

As well as its people, the other big assets in our research are our well-developed laboratories. We have excellent research facilities at the ANU and SUT that are maintained at world-class standards. Over the years we gained additional support from the Major Equipment grant committee of the ANU, special equipment grants at SUT and we twice received LIEF funding to be shared between ANU, SUT and UQ. We received financial support from the Defence Science and Research Organisation (DSTO) for the development of instrumentation for atom detection. Through this ongoing investment we can keep up with the technological developments in our research field and continue to be competitive on the global stage.

Commercialization

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 (IP). Such IP will be shared between the inventors and the host universities as defined in our IP agreement.

In particular the UQ and ANU groups are further developing the software code “eXtendable multi dimensional Simulator” (XmdS) http://www.xmds.org, which sees increasing use in research groups around the world. A significantly improved and updated version is now available under the new name xpdeint.

Participants of the ACQAO National workshop following ACOLS in Adelaide

Looking to the future

Throughout the course of 2009 the Centre worked closely with many interested parties to formulate plans for future research opportunities beyond the present funding cycle. We identified the grand challenges in both quantum and atom optics and selected the topic of precision measurements with ultra cold atoms as an area where our Centre can build world leading instruments and continue to be a drover for the advance technology of clocks, frequency standards and of interferometric measurement of gravitational gradients beyond the limits imposed by quantum physics. At the same time we can use the ideas and techniques developed in ACQAO for new simulations of real quantum systems and for fundamental tests.

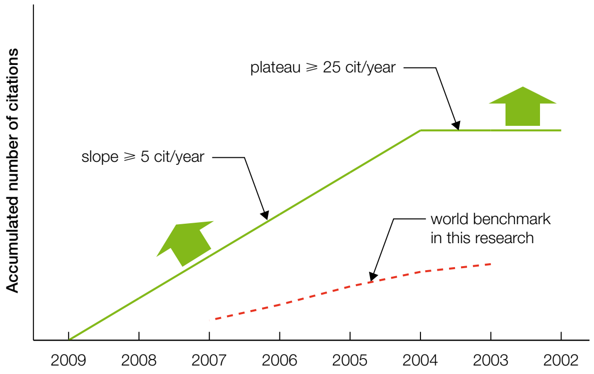
Key Performance Measures (KPMs)

The evidence for the excellent performance of our Centre is given by our Key Performance Measures (KPMs). These indicate both the quality and quantity of our research outcomes and the impact we have in training, on the research community and the wider public.

We are comparing our performance with the targets, initially set by the ARC in 2003 and then updated, and in several cases increased, in 2008. These targets set the expectation for world-class centres. We were able to not only meet all our targets but to exceed them in more than 60% of the categories by a factor of two or more. These results are summarised in the table on page 64 which show the KPMs for 2009, both the outcomes and the current targets, as well as the ratio between them. Performance that is higher than two times the target is highlighted in dark purple, and more than a factor of four is in blue.

Our Centre has not only produced outstanding results in 2009 but is also consistent in its achievements, in many cases remaining well above target performance over its seven years of operation. To document this we present the long-term achievement ratio, (last column in the table on page 64), which is the average of the achievement ratios over years of operation since 2003. This table shows that we consistently exceed our targets and initial expectations, again by more than a factor of 2 and 4.

Figure 2: ACQAO definition of citations for a high impact publication



Our Centre focuses on fundamental research and we publish our results in the public domain in internationally recognised journals. Our aim is to publish ahead of others and to make the highest possible impact in our research field. We have a thriving theory core that produces results at an ever-increasing rate with a continual growth in the number of citations received. The results of all our experimental projects have been reported in journals with the highest possible impact. Our publications include outstanding journals such as *Science, Nature*, *Nature Physics* and *Review of Modern Physics*.

We focus on the quality of our results and compare them to global benchmarks in our field of research. ACQAO has a special KPM that evaluates the impact of our publications. We have defined high impact publications as: those published in high impact journals (impact factor>5) and those that actually have a high impact with more than 5 citations per year or at least 25 citations total. Figure 2 shows this definition and also shows the world benchmark of our field as used in the ARC ERA process. Our definition exceeds the benchmark by a factor of about 2.5.

The steady increase in our productivity (see Figure 3) shows the total number of publications in comparison with our KPM target (red line). The peak is in 2008 — while we are presently working on our second set of ambitious research goals. The second feature is the number of high impact publications we produce. The rise from 2003–2008 is most impressive. In particular, our younger publications achieve a high impact and while it is still too early to measure the impact of our 2009 publications we can already see positive results.

Finally, the increasing number of joint publications demonstrates the increasing effectiveness of the interaction within ACQAO. The number of papers with co-authors from more than one node increased from none in 2004 to ten in 2009.

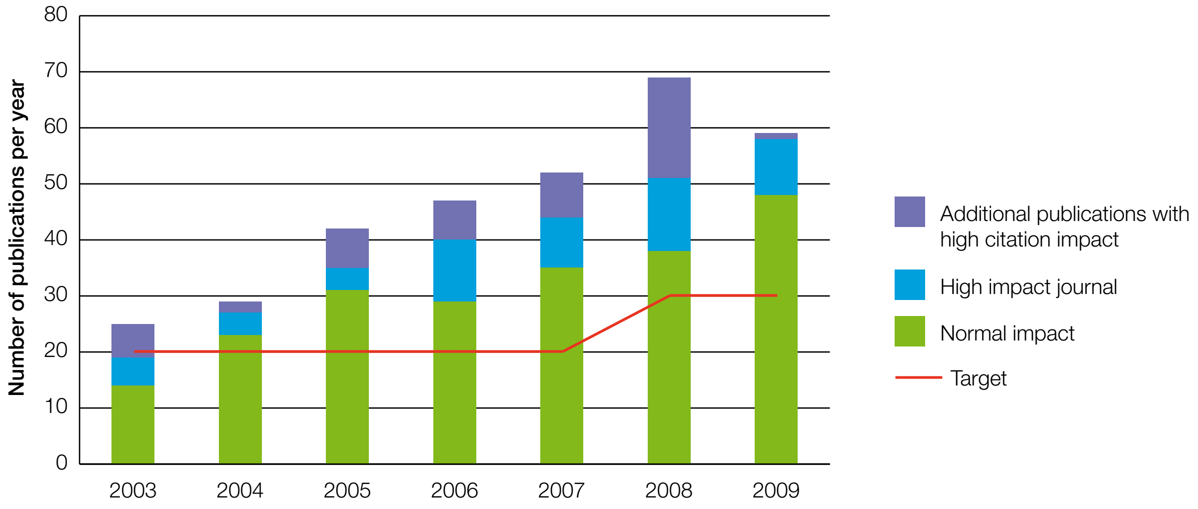
We are particularly proud of the international recognition our work receives, and the quality of our international links and networks. This is indicated by the impressive number of commentaries written about our results (31), the fact that about half of our 2009 publications (27) include international research collaborations, the large number of invitations (30) to ACQAO staff and students to present our research at conferences, visits to laboratories overseas (44) and the constant stream of international scientists and students who visit our Centre (15). Our staff actively contribute to many national and international committees (22) and we maintain a large number of active projects with international partners (26) each leading to joint publications, as shown on page 54.

Research training and professional education is one of our major strengths, with a good number of postgraduate students (7) completing their degree while even more have been recruited in 2009 (10). Many professional courses (22) and undergraduate courses (22) have been taught by our staff at all three host universities. In addition, we delivered a wide range of public awareness programs to the wider public (15), which are described in more detail on page 66.

The only area where our output is not exceeding the target is commercialization. We reached our target for patents and are actively looking for opportunities to create intellectual property for commercial use. From the ANU we actually manufacture and sell components for both research and education. However, the focus of ACQAO is on fundamental research for the public domain.

It takes time to build a Centre such ACQAO and we now demonstrate the positive effects of operating as a COE through the trends in our KPMs — Figure 4 shows the results normalised to the 2003 targets, for a number of categories. While the input, in terms of funding and number of people, has remained fairly constant, the outcomes and the recognition of our work has increased remarkably. This is evidence of the high impact of our Centre of Excellence.

Figure 3: ACQAO Publications



Key Result Areas and Performance Measures

Key Result Area	Performance Measure	Target	2009 Results	Achievement ratio 2009	Achievement ratio 2003–09
Research Findings and competitiveness	Quality of publications	6	11	1.8	2.7
	Number of publications	30	60	2.0	2.1
	Number of patents	0.3	1	3.3	1.9
	Invitations to address and participate in international conferences	5	30	6.0	4.8
	Invitations to visit leading international laboratories	8	29	3.6	4.4
	Number of commentaries about the Centre's achievements	3	32	10.7	2.9
	Additional competitive grant income (# applications submitted)	8	12	1.5	1.8
Research training and professional education	Number of postgraduates recruited/year	5	10	2.0	1.9
	Number of postgraduate completions/year	6	7	1.2	1.1
	Number of Honours students/year	5	6	1.2	1.3
	Number of professional courses	2	7	3.5	3.3
	Participation in professional courses	3	22	7.3	2.4
	Number and level of undergraduate and high school courses in the Priority area(s)	7	22	3.1	2.5
International, national and regional links and networks	Number of papers published with international co-authors/reports for internatioinal bodies	7	31	4.4	4.9
	Number of international visitors	15	15	1.0	2.1
	Number of national workshops/year	1	2	2.0	1.6
	Number of international workshops/year	1	1	1.0	1.6
	Number of visits to overseas laboratories	25	44	1.8	3.0
	Number of memberships of national and international professional committees	2	22	11.0	8.5
	Research projects with international partners	4	26	6.5	5.0
	Examples of relevant Social Science and Humanities research supported by the Centre	1	1	1.0	1.0
End-user links	Number of commercialisation activities	2	2	1.0	0.6
	Number of government, industry and business briefings	2	6	3.0	1.8
	Number of Centre associates trained/ing in technology transfer and commercialisation	1	2	2.0	1.5
	Number of Public Awareness programs	4	15	3.8	2.5
Organisational Support	Number of new Organisations recruited to or involved in the Centre	1	1	1.0	1.0

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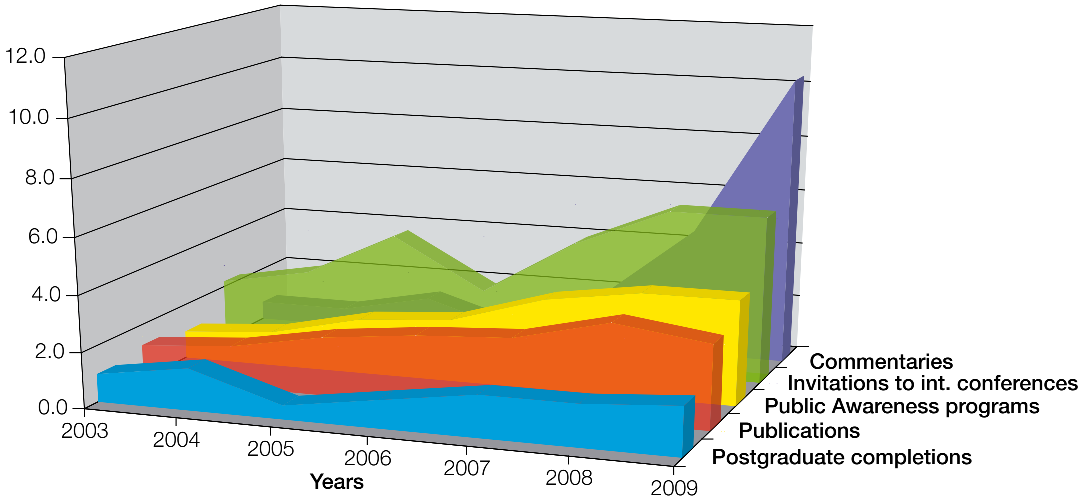
Figure 4: KPMs normalised to 2003 targets



Media, Outreach, and Awards

In 2009, ACQAO staff and students participated in a variety of outreach activities, received numerous awards and appeared in various media. Certainly the global developments in quantum science continue to receive widespread interest from the media. The media attention for the work of our Centre included a variety of print and web based articles and television appearances, each highlighting the public interest in this field of science.

Media

Media recognition for our work has been significant, with more than 40 articles being reported in local and national media. A small selection is shown on page 68. The most significant event in both media and outreach was the appearance of the Quantum Imaging team on the popular ABC show '*The New Inventors*'. The show invited the group to present their exciting results achieved in multimode entanglement (page 20). The group were awarded the episode winners on the night and the opportunity to showcase our work to the public in this unique way was a reward in itself. There was a real sense of interest in how our fundamental research is contributing to future innovations and in the potential major changes in our lifestyles.

A sample of the media coverage includes the following articles:

- Canberra Times

  The Atom-Light Entanglement group's work and Nature publication

  Professor Ken Baldwin and Professor Michele Thibier from the French embassy celebrating the close collaboration with French researchers.

  The Quantum Imaging group's work on Multimode entanglement

  The Atom Laser groups nomination in the 2009 Eureka prize

  TheHelium BEC group's work on measurement of the lifespan of the longest-lived excitable atom

- The Age

  The Molecular SUT BEC team's success with new experimental results

- The widely read German science magazines "Bild der Wissenschalt" and "Physik in unserer Zeit" carried full length stories about our work on optical entanglement.

- Web based coverage: the press release on multimode entanglement generated at least 11 stories on web pages in Australia and 30 international stories.

Part of the Quantum Imaging team on The New Inventors set

Outreach

A number of our staff and students contributed to outreach programs, presenting physics to school students across the countryside. In April, PhD student Sarah Midgley (ACQAO) with other UQ students, in conjunction with the UQ student chapter of the OSA (Optical Society of America), went on a physics outreach trip from Mossman to Townsville. In July, Michael Garrett visited schools in Northern Queensland presenting various entertaining physics demonstrations, and again as part of the ATSE Science Ambassador program. The response from students and teachers was very positive.

Dr Nick Robins and Dr Joe Hope continue to participate in the 'Scientist in Schools' program, both observing that young students have a real interest in science.

During Science Week 2009, Professor Ken Baldwin was invited to give a talk and demonstration about quantum physics at the Bega Library. This was well received with over 70 people from the public attending.

ACQAO was proud to once again support the students run workshop, KOALA, held at University of Sydney in November 2009. This proved to be a great success and highlighted the great young talent that Australia enjoys in our research field.

Professor Hans Bachor, along with several of our ANU PhD students, once again contributed to the National Youth Science Forum (www.nysf.edu.au). The program provides an excellent opportunity for year 11 college students from across Australia to explore their passion for science as a career for the future. All of these events allow us to promote ACQAO's achievements.

Awards

During 2009 a number of our students gained recognition for their work, demonstrating the exceptional quality of future leaders that ACQAO has had the privilege to train. Michael Garret (UQ Node) gained recognition for his work in winning the OSA prize for best student talk at the ACOLS conference.

Michael Garrett (UQ) awarded best student talk at ACOLS

Mahdi Hossini (Atom-Light Entanglement) and Kate Wagner (Quantum Imaging), were the only ANU PhD students awarded the CiSRA Prize for the best student research papers. These are publications in Nature and Nature Photonics listed in our publication list on page 54.

Sarah Midgley (UQ Node) was the 2009 winner of the Georgina Sweet Fellowship. This award recognises women in postgraduate research. Sarah certainly contributes enthusiastically to the field of physics.

Professor Bachor receives the AIP award for Outstanding Services to Physics in Australia

Professor Hans Bachor from the Australian National University was awarded the Australian Institute of Physics Award for Outstanding Services to Physics in Australia.

Dr. Nicholas Robins from the ANU atom laser group won the 2009 Young Tall Poppy Science Award, announced on 29th October. The award recognises early career researchers who have achieved significant scientific milestones. The selection is based on outstanding scientific research and a passion for communicating science to the wider community. Dr N. Robins, along with Professor J. Close and Dr C. Figl, were also finalists for the 2009 Eureka prize in the category Scientific Research for their work on "turning on the atom tap".

Bega Valley Shire Council

Media Releases

SAND IN THE PANTS: THE MICROSCOPIC WORLD OF QUANTUM PHYSICS

national science week 2009

August 4, 2009: Take the opportunity to find out more about the intriguing aspects of the quantum world and light waves during Science Week 2009 when Professor Ken Baldwin will give a talk and light demonstrations at the Bega Library.

It will prove to be a fascinating and engaging evening even for those of us not so "science-savvy".

Professor Baldwin is a laser physicist based at the Australian National University and won the Eureka Prize for Promoting Understanding of Science.

ABC Science

Researchers perfect quantum memory

Storing light information

Australian Research to Speed up Data Transmission

North Korea Times

Teleportation may soon be a reality!

theage.com.au

National

Cold waves

THE SCIENCE OF EVERYTHING

COSMOS

News

Quantum device stores pulses of light

SYDNEY: Australian researchers have demonstrated a way of storing quantum pulses of light that could be used in an optical memory device, similar to the way computers store and retrieve digital information.

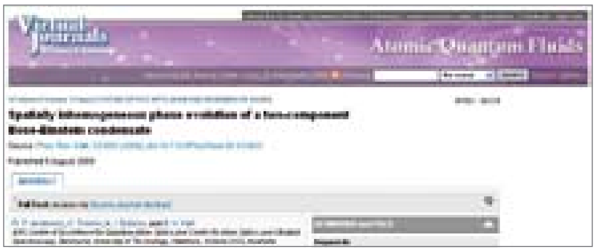
The technology, developed by a team at the Australian National University (ANU), in Canberra, also has applications in quantum cryptography, a secure means of communication that utilises properties of light to encrypt information.

Cryptography works if the information sender and receiver share a secret key.

Quantum repeater

"At the moment this is done by people travelling the globe carrying secret keys in briefcases," said team member and quantum physicist Ben Buchler.

"This works providing the guy with the briefcase isn't kidnapped. What quantum cryptography does is distribute the key, and you do that by using light," he said.



Virtual Journals

Atomic Quantum Fluids

Spatially inhomogeneous phase evolution of a two-component Bose-Einstein condensate

Physicists see the light in computing quest

The French connection

Scientists are forging links

"The language of science is universal, and in fact some of us learn French as a result."

Find may lead to better lights

Scientists get Eureka moment

SCI-TECH

Stopping the speed of light

Applications in computing

Thursday, August 13, 2009

Award for quantum leap in secure communication

BACK TO BASICS

2009 ACQAO Annual Report Finances

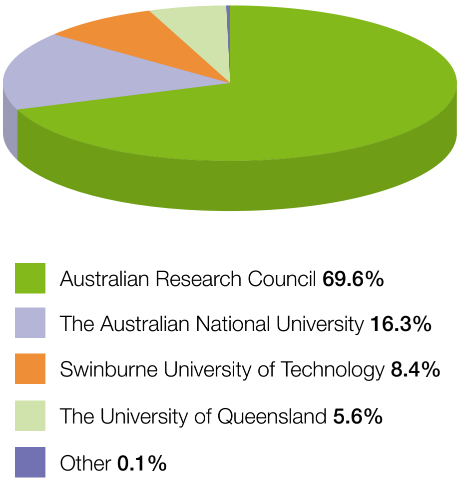
Accumulated funds	**$1,040,747**

ACQAO Income in 2009	
Australian Research Council	$2,123,456
The Australian National University	$499,000
Swinburne University of Technology	$257,133
University of Queensland	$170,000
Other	$2,947
Total Income	**$3,052,536**

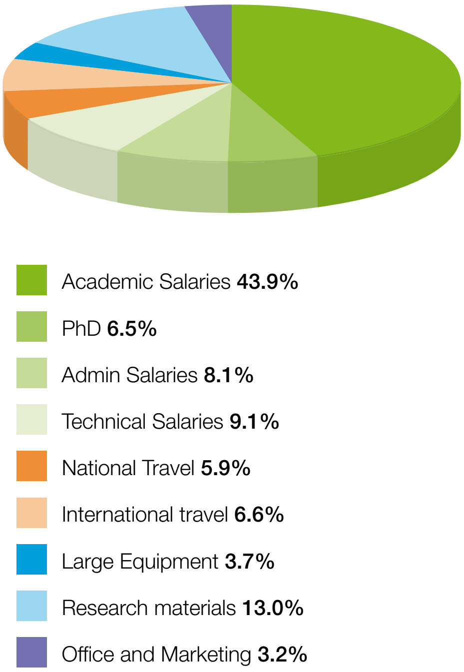
ACQAO Expenditure in 2009	
Academic salaries	$1,244,799
PhD	$185,162
Admin salaries	$230,703
Technical salaries	$256,687
National Travel	$166,749
International travel	$186,405
Large Equipment	$105,909
Research materials	$368,671
Operations & marketing	$89,918
Total Expenditure	**$2,835,002**

In-Kind contributions toward the Centre	
The Australian National University	1,214,621
Swinburne University of Technology	991,099
University of Queensland	362,853
Defence, DSTO	12,255
Australian Defence Force Academy	12,255
Total	**2,593,082**

ACQAO income 2009



ACQAO expenditure 2009



2009 Other research funding and grants for ACQAO, including ARC

Donor, title, staff	Gain to ACQAO
Australian Research Council, Federation Fellowship, Prof. Y. Kivshar	40,000
Australian Research Council, Discovery Project, Detection & Control of Ultracold Atoms, Dr J. Hope	110,000
Australian Research Council, Research Fellowship, Dr E. Ostrovskaya	97,000
Australian Research Council, Postdoctoral Fellowship, Dr Q. He	78,000
Australian Research Council, Postdoctoral Fellowship, Dr C. Ticknor	78,000
Australian Research Council, Postdoctoral Fellowship, Dr C. Lee	77,000
Australian Research Council, Queen Elizabeth II Fellowship, Dr Hui Hu	127,000
Australian Research Council, Discovery Project & QEII Fellowship, Continuous Variable Quantum Information Experiments, Prof. P.K. Lam	194,000
Australian Research Council, Professorial Fellowship, Prof. P. Drummond	41,000
Australian Research Council, Research Fellowship, Dr X Liu	49,285
Australian Research Council, Linkage International Fellowship, Dr CJ Vale, Dr M Mark, Prof. P Hannaford, Prof. R Grimm	90,000
Australian Research Council, Discovery Project, Universal quantum imaging, Dr WP Bowen, Prof HA Bachor, Dr N Treps (ACQAO component)	30,000
Australian Research Council, Postdoctoral Fellowship, Dr SA Haine	78,500
Australian Research Council, Postdoctoral Fellowship, Dr M. Matuszewski	90,000
Total	**1,279,785**

Personnel

ANU FAC NODE

Prof.	Hans-A.	BACHOR	Director
Dr	Ben	BUCHLER	CI
Prof.	John	CLOSE	CI
Dr	Cristina	FIGL	Research Fellow
A/Prof	Joseph	HOPE	CI
Mr	Damien	HUGHES	COO
Dr	Jiri	JANOUSEK	Research Fellow
Dr	Mattias	JOHNSSON	Research Fellow
Prof.	Ping Koy	LAM	CI
Dr	Nick	ROBINS	CI
A/Prof	Craig	SAVAGE	CI

STUDENTS

Mr	Sven	ABEND	Visiting Student
Mr	Paul	ALTIN	PhD
Mr	Seiji	ARMSTRONG	PhD
Mr	Justin	BEWSHER	Honours
Mr	John	DEBS	PhD
Mr	Graham	DENNIS	PhD
Mr	Daniel	DÖHRING	PhD
Mr	Julian	DUGUE	PhD
Mr	Mahdi	HOSSEINI	PhD
Mr	Michael	HUSH	PhD
Mr	Gordon	McDONALD	Honours
Mr	Jean-Francois	MORIZUR	PhD
Mr	Lachlan	NICHOLLS	Honours
Ms	Rachel	POLDY	PhD
Mr	Justin	SCHULTZ	Fulbright Scholar
Mr	Ben	SPARKES	PhD
Mr	Robin	STEVENSON	PhD
Mr	Stuart	SZIGETI	PhD
Ms	Katherine	WAGNER	PhD

ANU IAS NODE

Dr	Tristram	ALEXANDER	Research Fellow
Prof.	Ken	BALDWIN	Deputy Director/CI
Dr	Robert	DALL	Research Fellow
Ms	Kathleen	HICKS	Admistration
Prof.	Yuri	KIVSHAR	CI/Science Director
Dr	Chaohong	LEE	Research Fellow
Dr	Michael	MATUSZEWSKI	Research Fellow
Dr	Elena	OSTROVSKAYA	CI
Dr	Andrew	TRUSCOTT	CI

STUDENTS

Mr	Jasur	ABDULLAEV	PhD
Ms	Lesa	BYRON	PhD
Mr	Santiago	CABALLERO-BENITEZ	PhD
Ms	Kimberly	HEENAN	PhD
Mr	Sean	HODGMAN	PhD
Mr	Andre	STOFFEL	PhD
Mr	Ju-Kuei	WU	PhD

UQ NODE

Dr	Joel	CORNEY	Node Director/CI
A/Prof.	Matthew	DAVIS	CI
Ms	Stephanie	GOLDING	Administration
Dr	Simon	HAINE	Research Fellow
Dr	Karen	KHERUNTSYAN	CI
Dr	Murray	OLSEN	CI
Mr	Paul	SCHWENN	Technical Support

STUDENTS

Mr	David	BARRY	PhD
Mr	Chao	FENG	PhD
Mr	Andrew	FERRIS	PhD
Mr	Chris	FOSTER	PhD
Mr	Michael	GARRETT	PhD
Ms	Tania	HAIGH	PhD
Mr	Scott	HOFFMANN	PhD
Mr	Tim	LAMBERTON	Honours
Mr	Geoff	LEE	PhD
Ms	Sarah	MIDGLEY	PhD
Mr	Magnus	OGREN	PhD
Mr	Jacapo	SABBATINI	PhD
Mr	Andrew	SYKES	PhD

SUT NODE

Dr	Alexander	AKULSHIN	Research Fellow
A/Prof.	Bryan	DALTON	CI
Prof.	Peter	DRUMMOND	CI/Science Director
Dr	Brenton	HALL	CI
Prof.	Peter	HANNAFORD	Node Director/CI
Dr	Qiongyi	HE	Research Fellow
Dr	Hui	HU	Research Fellow
Dr	Leszek	KRZEMIEN	Research Fellow
Dr	Xia-Ji	LIU	Research Fellow
Dr	Michael	MARK	Research Fellow
A/Prof.	Russell	McLEAN	CI
Dr	Sung Jong	PARK	Research Fellow
Dr	Margaret	REID	CI
Dr	Wayne	ROWLANDS	CI
A/Prof.	Andrei	SIDOROV	CI
Ms	Tatiana	TCHERNOVA	Administration
Dr	Chris	TICKNOR	Research Fellow
Dr	Chris	VALE	CI

STUDENTS

Mr	Russell	ANDERSON	PhD
Mr	Paul	DYKE	PhD
Mr	Mikhail	EGOROV	PhD
Mr	Qiongyi	HE	PhD
Mr	Valentin	IVANNIKOV	PhD
Mr	Smitha	JOSE MOODAKUNNEL	PhD
Ms	Eva	KÜHNLE	PhD
Mr	Bogdan	OPANCHUK	PhD
Mr	Gopisankararao	VEERAVALLI	PhD
Mr	Holger	WOLFF	PhD

Previous ACQAO Annual Reports

The Australian Research Council Centre of Excellence for Quantum-Atom Optics
Annual Report for the year 2007

The Australian Research Council Centre of Excellence for Quantum-Atom Optics
Annual Report for the year 2008

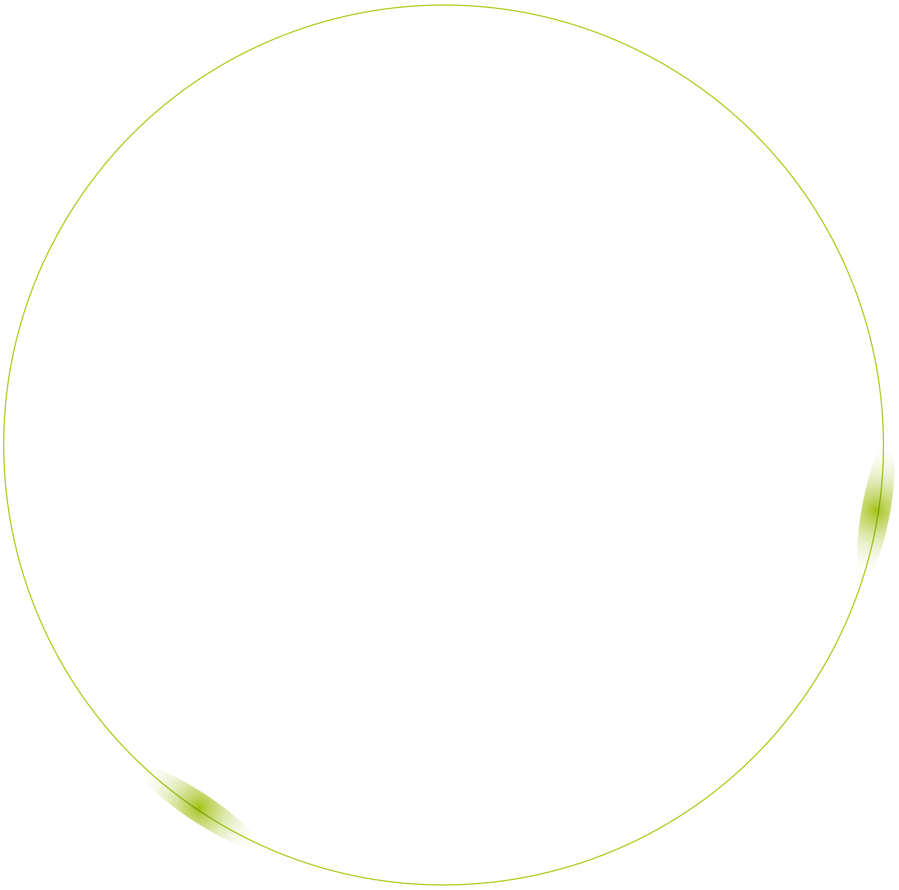
The Australian Research Council Centre of Excellence for Quantum-Atom Optics
Annual Report for the year 2006

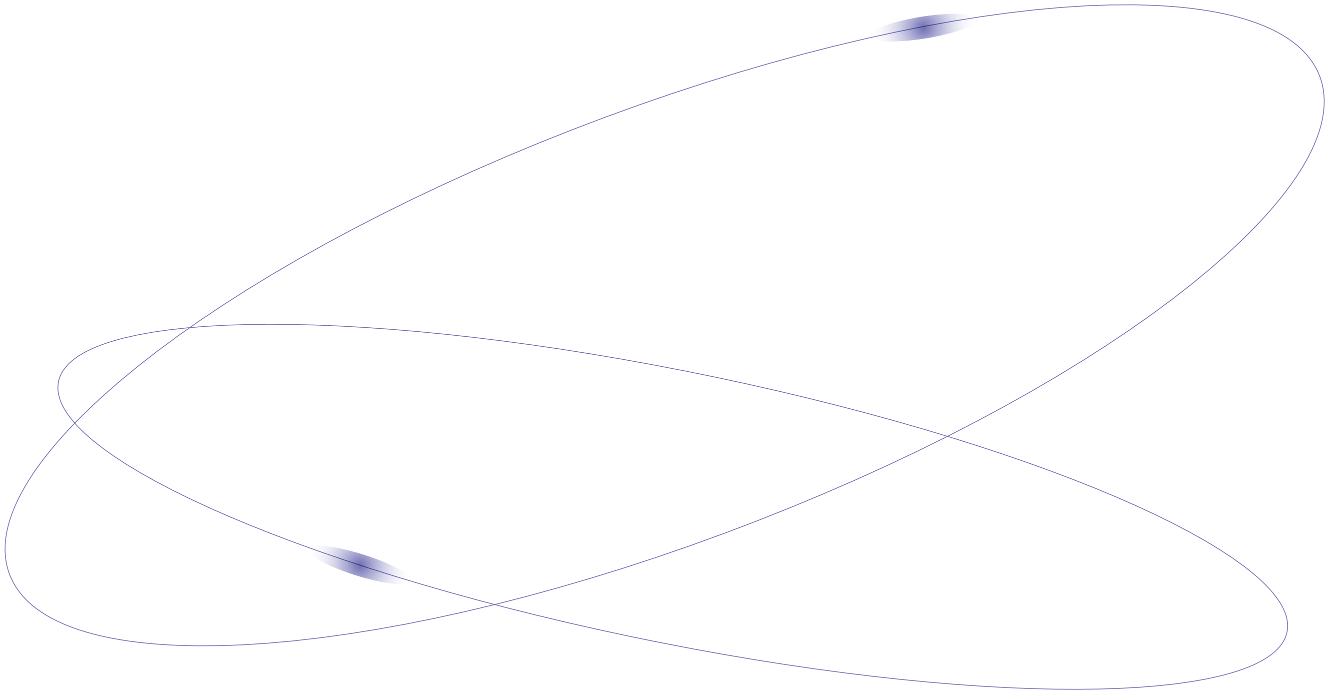
The Australian Research Council Centre of Excellence for Quantum-Atom Optics
Annual Report 2003

The Australian Research Council Centre of Excellence for Quantum-Atom Optics
Annual Report for the year 2005

The Australian Research Council Centre of Excellence for Quantum-Atom Optics
Annual Report 2004

Notes





Australian Research Council Centre of Excellence for Quantum-Atom Optics

http://www.acqao.org

Contact us:

Professor Hans-A. Bachor
Director
ANU FAC Node & Main office
The Australian National University
Department of Quantum Science
Level 1, Physics Link Building 38a
Science Road, Acton ACT 0200
T: 61 2 6125 2811
F: 61 2 6125 0741
E: Hans.Bachor@anu.edu.au

Professor Kenneth Baldwin
Deputy Director & IAS Node Director
The Australian National University
Research School of Physics & Engineering
Building 58, Cockcroft Building
Mills Road, Acton ACT 0200
T: 61 2 6125 4702
F: 61 2 6125 2452
E: Kenneth.Baldwin@anu.edu.au

Dr Joel Corney
UQ Node Director
School of Mathematics & Physics
The University of Queensland
Physics Annexe (Bld. 6)
Brisbane, QLD 4072
T: 61 7 3346 9398
F: 61 7 3365 1242
E: corney@physics.uq.edu.au

Professor Peter Hannaford
SUT Node Director
Faculty of Engineering and Industrial Sciences
Swinburne University of Technology
PO Box 218, Hawthorn, VIC 3122
T: 61 3 9214 5164
F: 61 3 9214 5160
E: phannaford@swin.edu.au

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