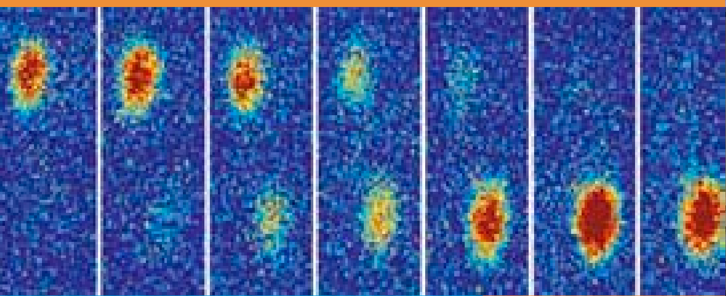

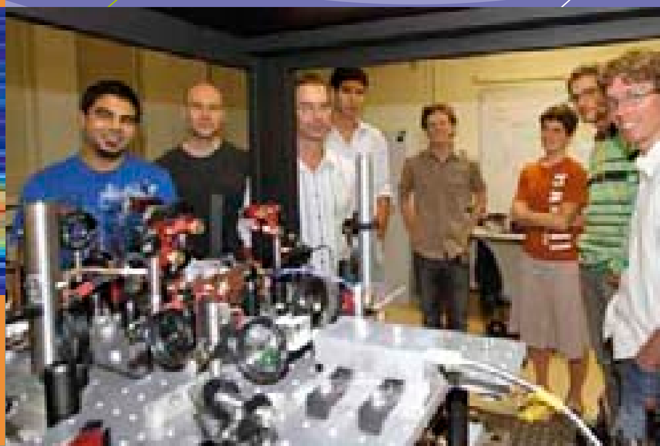

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report for the year 2010

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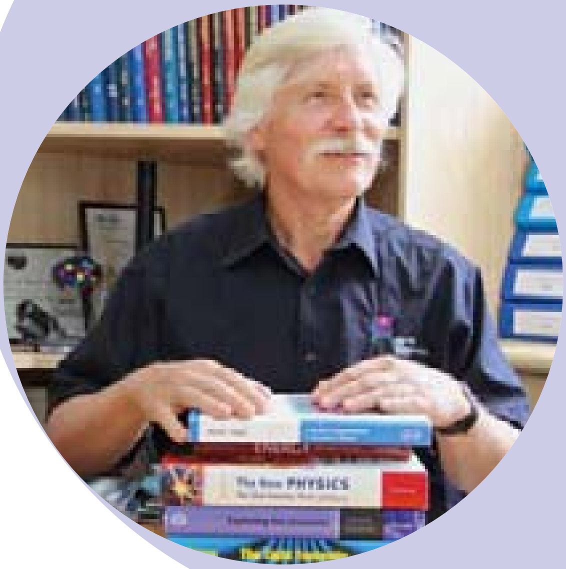
Foreword



Quantum-Atom Optics has become a driving force behind the development of future technologies. In a similar way that optics in lasers, semiconductors in computers have both shaped the way we live and work today; so too have quantum concepts. Within the next few decades, these concepts will influence and improve communication, sensing and metrology, navigation and computing devices, and other yet unknown areas.

The evolution of quantum technologies started with basic theory and Gedanken experiments in the 1930s. From there, we saw the first experimental demonstrations in the 1980s and 1990s, to the refined machines and theory models we have today and progressing to actual devices in 2020 – 2030.

In 2003, the Australian Research Council's Centre of Excellence for Quantum-Atom Optics (ACQAO) started to develop tools for future technologies, including novel ideas, in principle demonstration experiments and quantitative models. It has successfully accomplished this. In 2010, atom lasers, molecular BECs and universal laws for Fermi correlations, quantum memories and multimode entanglement are now a reality. In this way the Centre pioneered the science of multi-particle quantum effects within Australia.

ACQAO achieved this through combining the best research groups that use ultracold atoms with those using non-classical laser beams with large numbers of photons. ACQAO pioneered the concept of national collaboration, as part of the first generation of Centres of Excellence. We started with ambitious goals, in both theory and experiments, and succeeded in achieving each and every one of them. We created a coherent research team that combined the skills across the nation in areas that operated individually and as a Centre. ACQAO has attracted the attention and admiration of the global research community in quantum and atom optics.

At the same time, we have trained a group of outstanding young scientists, who have now advanced to operating their own research programs, holding Fellowships and leading new research teams. They will take our research to the next level across the world. ACQAO was a transition from purely fundamental research to a set of advanced research topics managed by well-established research teams, and in some cases as part of newly formed Centres of Excellence.

ACQAO has achieved its mission of linking the diverse techniques of optics, photonics, ultracold atoms and coherent matter waves. Our strength is that we can demonstrate the special quantum properties of larger objects, involving thousands or even millions of atoms and photons, and observe the link between the microscopic worlds of few particles to the macroscopic classical world. In some cases, we were able to do this first – amongst a lively group of collaborators and competitors across many countries.

ACQAO combines the skills and experience of many of the most productive Australian researchers in this field. We brought together experienced research leaders with successful younger scientists and included a highly talented and motivated group of graduate students.

In addition to the Australian Research Council (ARC) support, our Centre is thankful for the support of the Australian National University (ANU) in Canberra, the University of Queensland (UQ) in Brisbane and Swinburne University of Technology (SUT) in Melbourne.

We have enjoyed close, intensive collaboration with a number of the leading groups in the world, initially with five partners in Europe, and now with more than ten partners covering Europe, United States and the Asian region. We had a whole series of scientific exchanges with staff and students working at different locations, linking ideas and expertise.

Our scientific workshops have been an exemplary success, in both Australia and Europe, giving our younger scientist great opportunities to develop personal networks and allowing them to work effectively across international borders. As a result, the visibility of Australian science has increased significantly.

In addition to our ever-expanding collaboration network, ACQAO has created significant scientific links. Combining the concepts of quantum statistics for bosons and fermions and their nonlinear interaction, with the operation of non-classical light sources, Bose-Einstein Condensates (BECs) and atom lasers.

The highlights for 2010 reported here are numerous and include;

- The optimisation of atom lasers in Rb and He*,
- Measurement of the third-order correlation function $G^{(3)}$ for He*,
- The first image of atomic speckle with corresponding second-order incoherence,
- Quantum noise limited matter wave interferometry,
- The study of correlations in Fermi gases and the testing of universal theories for Fermions,
- Record setting efficiencies for quantum memories in atoms,
- Major improvements in the entanglement of co-propagating laser beams and multimode entanglement,
- The dynamics of ultra-cold Bose gases and,
- A theory of vortex formation in a BEC.

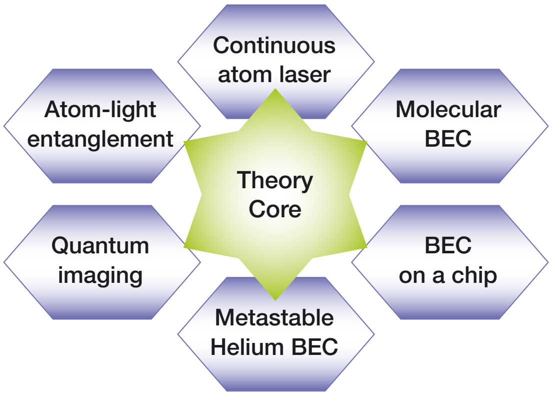
The long-term investment, over 8 years, in people and laboratories has paid off in an impressive way. After achieving our initial goals, set in 2002, we have in the last two years concluded our second generation of projects, which align with, and in some cases influence, the international agenda in quantum physics. Our expanded links in Australia now include researchers from Griffith University, Monash University and the University of Western Australia. Through this network, the formulation of the big strategic ideas for the future of science with ultra-cold atoms is taking place, covering important strategic goals in quantum metrology and quantum emulation.

In summary, we demonstrated the effectiveness of the concept of an ARC Centre of Excellence and advanced the knowledge in Quantum and Atom Optics significantly. I trust that this report, with a strong focus on the details of the science and the people who created it, stimulates your interest in our successful quest to create the scientific tools for future quantum technologies.

Hans-A. Bachor

Professor Hans-A. Bachor
Director

Quantum-Atom Optics — background and achievements



ACQAO 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 get around 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. We have applied this concept not only to light [p.40] but also to atoms [p.50]. One example is to reduce the uncertainty in the measurement of the phase of the atomic wave function to the quantum limit [p.27] and, in the future, below this quantum limit [p.29].

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 wave-like 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 and demonstrated atom lasers that produce coherent matter waves and we can now study the quantum statistical properties of atoms in a way similar to optics [p.18]. This opens the way for new examples of quantum technology, such as improved sensors based on atom interferometry [p.28], 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 a molecular Bose-Einstein condensate (BEC) and to investigate the properties of strongly interacting 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 by 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. 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.40].

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 is investigating the properties of EPR entangled matter beams [p.19].

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. This 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 comprised of atoms in two spin states. 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.34] and superfluidity in BECs [p.32]. Working with the University of Otago, they extended the usefulness of “classical field” methods for describing quantum and thermal dynamics, statistical mechanics and topological defects of Bose gases [p.33].

Australia now has eight operational BEC experiments, five in Rubidium 87, and one each with Rubidium 85 metastable Helium and Lithium. All are optimized 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 important atom optic components, which can be found in devices used for applications such as atom holography and matter wave interferometry.

After our demonstration of the pumped atom laser in 2008, one ANU team compared different types of output couplers to increase the atom flux and improve the beam quality. This has now been expanded to build the key components required for atom interferometry [p.28].

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. A second ultracold metastable Helium facility is used to perform fundamental tests on atomic structure and to test the theory of Quantum Electrodynamics (QED).

From Bosons to Fermions

Recent years have seen a very rapid development of the theory concepts and complex experiments with fermions. A new major highlight is the theory of strongly interacting, ultra-cold fermions. A major breakthrough is the study of the universal properties of a Fermi gas [p.20] and the application of this theory from Australia to experiments performed by our collaborators overseas [p.31].

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 detailed investigation of the properties of two dimensional 6Li Fermi gas using Bragg scattering [p.21].

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 gradient photon echoes for storing and retrieving quantum information has been very successful in delaying and storing and reordering information with extremely high efficiency [p.37] complementing the work in solid state materials.

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-renowned researchers. The different techniques and expertise from quantum optics, field theory and non-linear optics are combined within one powerful group of scientists who guide and support the experimental work. In some cases the theory is well ahead of the experiments.

Outstanding examples can be seen in our work on macroscopic self-trapping of ultracold Bose-Fermi mixtures [p.24] 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 technological and commercial progress and are performed at the ANU outside this Centre, and around the world. Other strategic topics, such as global precision time metrology and the implementation of satellite based atom interferometers for remote gravity sensing, will follow. As a Centre of Excellence our goal is to create new ideas, experimental demonstrations and simulations and to become a partner in such large scale, global frontier projects. Our work over the next eight years will pave the way for applications of quantum technology within 10 - 15 years.

ACQAO has built its success by combining separate scientific concepts, linking the leading scientists in Australia and maintaining a lively exchange with our partners in Europe and New Zealand. Our collaborations include some of the leading groups in the field, such as IFRAF in France and QUEST in Germany. In this way, ACQAO played an important role in the global research effort to ensure that future optical and atomic quantum technology continues to be developed and most importantly to remain accessible to Australia.

Research Highlights

Project – Quantum Imaging

Professor Ken Baldwin

Professor Ken Baldwin is Deputy Director of ACQAO. He undertook the first atom optics experiments in Australia in 1988, and in 1994 founded the metastable helium atom optics research programme at ANU. In 2010 he was awarded the Barry Inglis Medal by the National Measurement Institute for his career contributions to excellence in measurement science by an individual in Australia.

The ultracold metastable helium project is a foundation programme of ACQAO which aims to investigate the quantum statistical properties of quantum gases. Metastable helium is important in atom optics and precision measurement because of the ability to detect single atoms as a result of their large stored internal energy [1], and is an ideal candidate for experiments on quantum statistics.

2010 has seen the culmination of this programme, leading to a milestone experiment which has demonstrated that a BEC is coherent up to third order (g^3) in the correlation function [2]. First order coherence is exemplified by interference between condensates, and second order coherence is manifested in the Hanbury Brown and Twiss effect (also demonstrated in our laboratory - [3]). Our experiments are the first to show that BECs are characterised by higher-than-second-order coherence, lending support to the long-held conjecture that condensates – like the laser – are coherent to all orders.

We have extended this work to investigate the quantum statistical properties of incoherent matter wave sources. Building on our development of single- and multi-mode waveguides for atomic de Broglie waves [4], we have made the first images of atomic speckle (a property of second-order correlations) [5]. We have demonstrated that the speckle pattern associated with multi-mode matter waveguiding is also characterised by atom bunching – a signature of second-order incoherence.

The success of these investigations is built around a highly stable and reproducible metastable helium BEC machine combined with a leading-edge, high-resolution detection system. This apparatus will enable future studies of even higher-order correlation functions, and will test of the foundations of quantum mechanics by investigating entanglement and non-locality.

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Project – Atom laser project page

Dr. Nick Robins

Dr. Nick Robins completed his PhD at the ANU and has been part of ACQAO from the start. He was awarded an ARC APD Fellowhip in 2004, and became an ARC QEII fellow in 2010. Dr. Nick Robins leads the atom laser program together with Prof. John Close.

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 a ^{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. Raman lasers have inherently less classical noise, a higher maximum flux, and a beam profile that is closer to the quantum limit than 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.

For our group, 2010 was a year of atom interferometry. We began the year with a massive collaborative project between our experiment at ANU and theoretical work at Monash University, University of Queensland and the Joint Quantum Institute in the US [7]. We then went on to demonstrate a free-space gravimeter utilising a Bose-Einstein condensate and large momentum transfer beam, splitting [8]. These results open the door to the application of BEC's and atom laser's to precision inertial sensing.

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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 2006, he became a Professor (Chair) of AMO physics at Renmin University of China. He was awarded an ARC QEII Fellowship in 2009 and relocated to Swinburne University. Recently, he was promoted to associate professor.

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 experimental teams at Duke (John Thomas) and Rice University (Randy Hulet), we developed several powerful tools, including a strong-coupling diagrammatic theory [1], whose accuracy was experimentally confirmed [2, 3], and the use of exactly solvable models to predict an exotic superfluid phase [4], which was observed at Rice [5]. 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 Swinburne University (Chris Vale), we address issues that are crucial to understand and engineer the superfluidity in the strongly interacting regime.

In 2008-09, we focused on the development of a controllable quantum cluster expansion theory and demonstrated its wide applicability in a trapped, strongly interacting quantum gas [6]. Our theoretical prediction of expansion coefficients was soon confirmed by Salomon's group at ENS Paris [7]. In 2009-10, we extended this technique to dynamic properties and solved completely the high-temperature problem in the strongly interacting limit [8]. We also predicted new Fermi universality law on the structure factor, which was confirmed recently at CAOUS [9], Swinburne University, which is one of ACQAO nodes.

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.

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Project – Strongly interacting Fermi superfluids

Dr Chris Vale

Dr Chris Vale joined the cold molecules group at Swinburne at the beginning of 2007, shortly before the group produced their first molecular BECs. In 2008, Chris became project leader of the molecular BEC program in ACQAO and has been in that role since then. He played a key role in applying Bragg spectroscopy to Fermi gases and is now pursuing the study of 2D Fermi superfluids.

Researchers in the cold molecules laboratory of ACQAO at Swinburne have recently made a number of important breakthroughs in understanding of strongly interacting Fermi superfluids. Using Bragg spectroscopy they have been able to investigate a number of universal aspects of strongly interacting fermionic superfluids. These findings apply not only to ultracold Fermi gases in the Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) crossover, but to all dilute fermionic systems when the characteristic length scale of interactions exceeds the inter-particle separation.

This research began in 2003 when it was discovered 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 followed soon after. Fermi gases near Feshbach resonances provide a textbook realisation of the BEC-BCS crossover, a well known paradigm in condensed matter physics due to its connections with superconductivity [1]. Following the successes demonstrated with fermion-fermion molecules, and the prospects for gaining further understandings of the BEC-BCS crossover, the Swinburne group decided to pursue the ambitious goal of producing a molecular BEC with ^{6}Li atoms, which they achieved in 2007 [2].

In 2008, the Swinburne group performed the first experiments using Bragg spectroscopy to study pairing through the BEC-BCS crossover [3]. These results were widely cited as they provided quantitative results on pair correlations. Since then, in close collaboration with theorists within ACQAO (also at Swinburne) we have demonstrated a number of developments including the demonstration and measurement of universal short-range pairing [4]. They have also used Bragg spectroscopy to measure both the interaction and temperature dependence of the universal contact parameter [5,6]. These studies are now being extended towards lower dimensional systems where we have just demonstrated the crossover from 3D to 2D and seen the emergence of shell structure in the growth rate of the cloud density [7].

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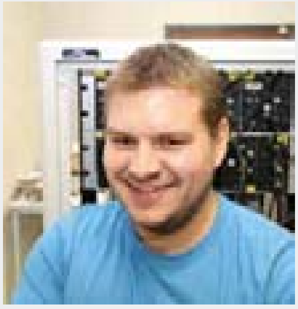
Project – Quantum Imaging



Dr Jiri Janousek,
Postdoctoral researcher, since April 2008

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. This device opens an avenue for building complex programmable quantum networks in the spatial domain.

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]. In 2010, we developed techniques to generate and control the process of entanglement using spatial light modulators, and showed that the mode of the squeezed light can be transformed into higher-order Hermite-Gauss modes efficiently using a universal programmable mode converter [4,5]. The programmable nature of the mode converter makes it a flexible device, allowing, for example, the same quantum resources and optical setup to be used for a wide range of quantum-enhanced detections.

We have also built a simple, elegant apparatus that can generate, control and detect a beam with multiple modes. These modes carry quantum information in the form of cluster states or other higher order forms of entanglement. The scheme is based on a multi-pixel homodyne detection that allows to access quantum correlations of spatial modes propagating within a single beam of light. More importantly, the scheme allows various quantum networks to be coded, controlled and optimized using a computer without a need to change the optical setup.

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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.

The atom-light entanglement program has developed a new form of coherent optical memory. The gradient echo memory (GEM) was in collaboration with the group of Dr. Matthew Sellars [1]. The original two-level scheme has been extended to three level atomic ensembles where we have realised 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 electromagnetically induced transparency (EIT). Substantial delay of squeezing was achieved along with the first demonstration of transmission of biased entanglement through EIT [4].

Between 2008 and 2010, we focused on the GEM system. We extended the technique to three-level atomic systems [5] and also showed that the memory can be described as a normal mode system in Fourier space [6]. It was this picture that enabled us to design the random access quantum memory [2] and a proposal for frequency filtering [7]. Our memory is now the most efficient quantum memory candidate so far demonstrated with recall of up to 87% [8] and we have plans to extend the system to cold atomic ensembles [9] to improve storage lifetimes.

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Project – Theory of correlations in quantum-atom optics

Dr Karen Kheruntsyan

Karen Kheruntsyan is a CI and a founding member of ACQAO. He served in the role of Deputy Director of the UQ Node in 2004–2006. Kheruntsyan leads the theoretical programs on atom-atom correlations in 1D Bose gases, molecular dissociation, and condensate collisions. He was awarded an ARC CoE Fellowship in 2005 and an ARC Future Fellowship in 2010.

The theory and measurement of correlation functions is one of the central themes in the study of ultra-cold atomic gases. By probing complex many-body states of these interacting quantum systems, correlation functions facilitate the most in-depth understanding of the underlying physics, not accessible through the simple density-profile measurements and mean-field theoretical descriptions.

One of the 2010 highlights in this research stream was the production of a source of pair-correlated atoms that beats the standard quantum limit on noise [1]. The correlated atoms were generated by colliding two Bose-Einstein condensates of metastable helium [2] and were shown to possess sub-Poissonian fluctuations in the relative atom number. The condensate collision experiments were performed in the ultra-cold atom laboratory of Profs Chris Westbrook and Alain Aspect of the Institute d'Optique – member of the ACQAO partner institute IFRAF in France. Dr Kheruntsyan, alongside with Dr P. Deuar of the Institute of Physics, Polish Academy of Sciences, have provided theoretical support to these experiments.

Another 2010 highlight was the first measurement and theoretical characterization of the third moment of density fluctuations in a 1D Bose gas [3]. In collaboration with Dr Isabelle Bouchoule's group of the same Institute d'Optique, Kheruntsyan and his colleagues have shown that such measurements reveal the presence of three-body correlations and constitute a very sensitive probe of the thermodynamic equation of state of the gas, applicable to other ultra-cold atom systems.

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Project – Coherence of BEC on Atom Chip

Professorial Fellow Andrei Sidorov

Andrei Sidorov is a CI and a founding member of ACQAO. He is leading the Atom Chip project, teaches a number of undergraduate courses and supervises four PhD students at SUT.

2010 was an interesting year with two major breakthrough developments in our research: one in studying ultracold interacting bosons and the second is with interacting fermions. Back in 2003 we set an ambitious aim to study coherence of a macroscopic quantum object, a Bose-Einstein condensate, using microfabricated magnetic-field generating structures – an atom chip. Matter wave interferometry is a powerful method for sensitive measurement and improving the precision of measurements requires preservation of coherence and long phase accumulation times.

It is widely considered that atomic interactions destroy coherence in BEC and play a detrimental role in matter-wave interferometry. In 2008 we observed a relatively fast decay of interference fringes in a two-component condensate due to the imbalance between inter- and intra-particle interactions and the associated spatial dephasing of the condensate [1]. We have now observed ([2] and page 26) remarkable rephasing and periodic revivals of the interference contrast related to the collective oscillations of the BEC driven by mean-field interactions, confirming that all condensed atoms share the same macroscopic wavefunction. By employing a synchronised spin echo technique we observed that in a BEC of 44,000 interacting atoms the revived contrast reaches 75% at the long evolution time of 1.5 s, implying an unprecedented coherence time of 2.5 s.

In 2010 I was also directly involved in a collaborative project on heteronuclear mixtures of quantum degenerate fermions at the Institute for Quantum Optics and Quantum Information, Innsbruck, Austria. Using a high degree of experimental control we created an ultracold Fermi-Fermi mixture of ^{6}Li and ^{40}K to explore a highly desirable regime of strong interactions [3]. In the centre of the interspecies Feshbach resonance two distinctive hydrodynamic phenomena with well pronounced features were observed. The characteristic inversion of the aspect ratio was accompanied by a collective drag whereby the two species stick together and expand with the same flow velocities. These observations in strongly interacting ultracold atoms will be of great interest to similar quantum systems in other branches of physics, including condensed matter, neutron stars and high-energy particle physics.

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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, Research School of Physics and Engineering, 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 ACQAO our group 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].

Further, we concentrated on the controlled manipulation and transport of matter waves in ultracold atom-guiding structures created by optical and magnetic traps, which could be potentially useful for future applications of utracold atoms in atomic interferometry and quantum information processing. In particular, we have demonstrated mass-dependent transport of BEC in an optical ratchet potential [4] and dynamical routing of BEC wavepackets through an optical lattice [5]. Most recently, we have been focusing on the physics of orbital angular momentum in the ultracold atomic systems and its role in stabilisation and dynamics of matter waves [6].

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Project – Atom laser theory

Joe Hope

Joe Hope was a founding CI of ACQAO, with a strong interest in atom lasers and their limits and possibilities. Joe 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 and the efficient simulation of high-dimensional systems undergoing measurement-based feedback.

In 2010, the atom laser theory group at the ANU continued to develop tools for understanding the quantum control of large quantum systems. This included creating fast, approximate methods for designing and modelling quantum networks [1], using feedback to stabilise entanglement generation [2], and determining the effects of interactions on a feedback scheme for an atom laser [3]. This long-term development occurred alongside continued support for the active experimental atom laser program, where we analysed the transverse mode imaging of guided matter waves, bosonic correlations in atom lasers [4] and the generation of directional coherent matter beams via dynamical instabilities in Bose-Einstein condensates [5].

We also discovered and examined a new class of stochastic methods based on a number-phase Wigner representation. These methods are the only strong candidate for the simulation of many classes of large quantum systems, specifically those with strong nonlinearities or those described by conditional states [6]. We also showed that the dynamics of entanglement in decaying systems can be fully quantified by monitoring the photons emitted by the system to the environment [7].

The group has worked with all three ANU-based experimental projects within ACQAO, and examined a range of theoretical topics, developing new theoretical and computational techniques and tools. Throughout the time of ACQAO we enhanced the understanding of the properties of atom lasers. 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. 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 took the main role in providing theoretical tools for the atom-light entanglement project, including an examination of the existing quantum memory schemes. In collaboration with the UQ theory node, we 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 proposing a measurement-based feedback experiment for the atom laser experiment, examining limits on quantum memories, supporting both ANU BEC experiments, and investigating the use of optimal ultrafast gates in ion traps.

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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 combines 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.

International Advisory Board members

Professor Alain Aspect, Institut d'Optique, Palaiseau, France.

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.

National Advisory Board members

Professor Lawrence Cram, Deputy Vice-Chancellor, The Australian National University.

Dr Mark Dransfield, Chief Geophysicist, Fugro Airborne Surveys Pty Ltd..

Dr Steven Duval, Technology Consultant.

Dr Peter Fisk, General Manager: Physical Metrology, National Measurement Institute

Department of Innovation, Industry, Science and Research.

Dr Warren Marwood, Research Leader, RFEW, Electronic Warfare and Radar Division, Defence Science and Technology Organisation (DSTO).

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. The Centre regularly monitors its progress against the key performance measures (KPM) and international benchmarks. Our achievements measured as KPM's are described in detail on page 60. 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 and SUT).

Throughout 2010, the Centre held several 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.

In addition to regular operational meetings, ACQAO hosted a series of meetings in the first half of 2010 as part of future planning and the development of a new ARC Centre application. These meetings combined as both increased opportunity for CI's, Executive and Advisory board members to discuss scientific direction, and allowed for new collaborations to be forged with the University of Western Australia and Monash University.

Hans Bachor presenting to the International Advisory board and special guests at the July CI meeting

Figure 1. ACQAO meetings 2010

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

Cape Tribulation student workshop participants, July 2010.

Direct Measurement of the Third Order Correlation Function for Ultracold Quantum Gases

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

One of the seminal advances in quantum optics was the understanding that a quantised description of ensembles of photons could be characterised by first, second and higher order correlations. These properties correspond to single photon density, two-photon coincidence (bunching or anti-bunching), three-photon coincidence and so on.

Correlations are also a fundamental property of matter waves, and the single wavefunction that describes a Bose-Einstein condensate (BEC) is in principle characterised by long range coherence to all orders (i.e. a universal correlation value of unity). By their very nature higher order correlations are difficult to measure, due to the vast amounts of data required. Higher order correlations have been shown for photons [1], but only first order [2] and second order [3] correlations have been directly measured for matter waves, even though the effect of third order correlations on 3-body loss rates has been shown to be important [4].

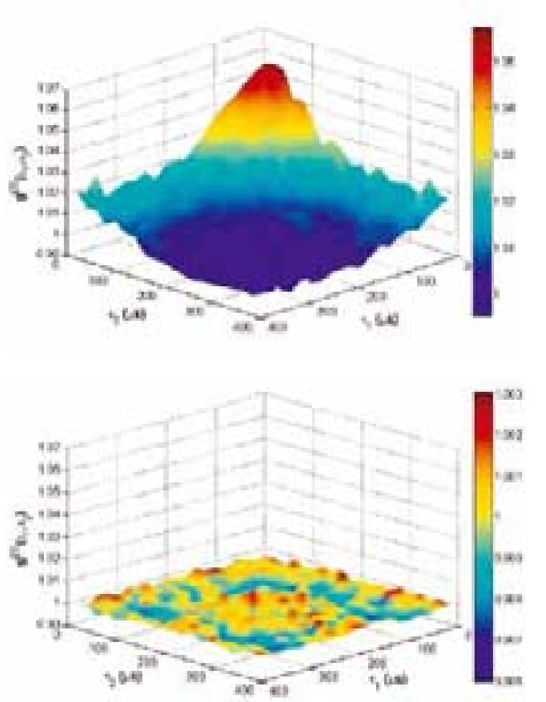

Figure 1: Third order correlation function for (upper) an ultracold thermal gas and (lower) a BEC.

In this experiment we demonstrate the first direct measurement of third order coherence for matter waves [5] (Fig. 1). Further, we show that the ratio of the second order to third order coherence for zero delay between the particle arrival times is consistent with theoretical predictions.

We exploit the unique single particle detection capabilities of metastable helium (He*) atoms made possible by our novel experimental process to study the correlation properties of ultracold atomic gases above and below the BEC critical temperature. Above condensation, where the atomic cloud behaves like an ensemble of incoherent sources, we observe bunching behaviour for both second order g(2)(τ_1) and third order g(3)(τ_1,τ_2) particle correlation functions. Below the critical temperature, the two correlation functions are both unity for all values of the delay between the particle arrival times, as expected for the long range coherence that characterises a BEC, see Fig. 1 (lower).

The ratio of the amplitude for thermal atoms of g(2)(0) and g(3)(0,0), which we measured to be 2.95 +/- 0.1, provides an absolute test of the higher order coherence properties.

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Generation of entangled particle beams

Graham Dennis[1] and Mattias Johnsson[1,2]
[1] *Research School of Physics and Engineering, Department of Quantum Science, ANU*
[2] *Research School of Physics and Engineering, ACQAO, ANU*

One of the most fundamental properties of quantum mechanics is non-locality, meaning the measurement of a quantum state in one location can have an instantaneous effect on another state that is arbitrarily distant. This property has been tested with light via EPR entanglement, but tests using particles with mass have not yet been carried out. Our contribution towards this goal has been to develop and analyse a system which provides the resources to carry out such a test.

As part of previous work in ACQAO, we have examined a system where an atom laser was generated from a metastable helium (He*) Bose-Einstein condensate (BEC). We showed that when the coupling between the atom laser and the BEC was sufficiently large, the transverse profile of the atom laser developed well-defined "peaks". These peaks arise from two conical beams of particles being emitted along the long axis of the BEC (see Figure 1).

These cones are generated via a novel four-wave mixing process that relies on the s-wave scattering rates for the two atomic species in the BEC being different. In our system this leads to dynamic instabilities in the BEC, which are exponentially amplified at specific momenta [2]. A 1D truncated Wigner simulation of a He* BEC is displayed in Figure 2, showing how specific momenta along the long axis of the BEC become heavily populated over time.

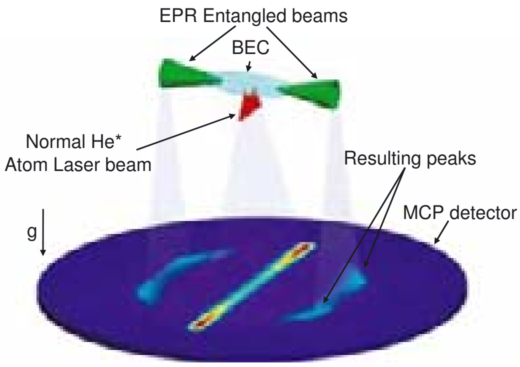

Fig. 1: Transverse atom laser profile

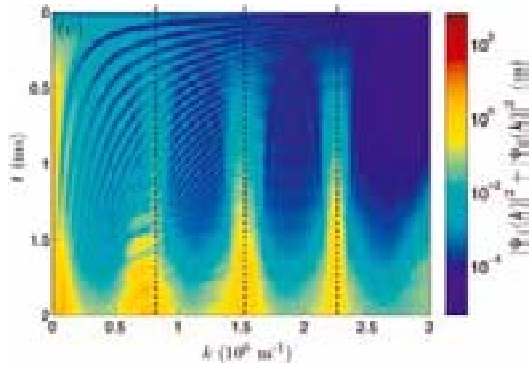

Fig. 2: Amplification at specific momenta (simulation)

The evolution of the fluctuation operators describing these momenta are given by [2]

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

which are identical to those governing degenerate parametric down conversion (PDC) in optics. Consequently, just as PDC is a source of EPR-entangled photon pairs, the cones in our system consist of EPR-entangled atom pairs.

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Universal contact parameter of a strongly interacting Fermi superfluid

E. D. Kuhnle, P. Dyke, S. Hoinka, M. Mark, H. Hu, X.-J. Liu, 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 systems 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 and as such form model systems to study universal behaviours. In 2005 Shina Tan [1] developed several exact relations for two component Fermi gases in the BEC-BCS crossover, which connect the bulk thermodynamic properties to the microscopic parameters through a single short-range parameter known as the contact, $\mathcal{I}$.

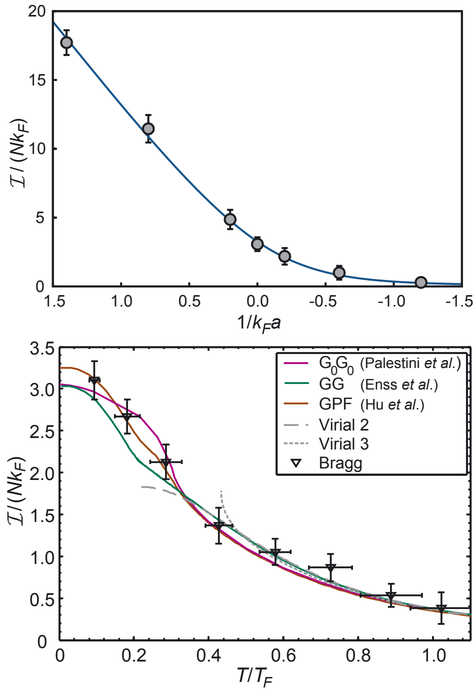

Figure 1: Universal contact parameter $\mathcal{I}$ measured as a function of (a) the interaction strength $1/(k_F a)$ and (b) the reduced temperature T/T_F at unitarity.

Previously, we have verified that pair correlations in a strongly interacting Fermi gas follow Tans universal law [2]. More recently, we have used the universal relation for the static structure factor below, to measure both the interaction and temperature dependence of the universal contact.

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

where N is the atom number, k_F is the Fermi wavevector, k is the probe wavevector 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 that $S_{\uparrow\downarrow}(k >> k_F)$ can be measured with high momentum transfer Bragg spectroscopy [3].

we can use the above equation to obtain the contact as shown in Fig 1(a) on the side. Also shown is a theoretical calculation based on a Gaussian pair fluctuation theory for strongly coupled Fermi gases [4]. The predictions and measurements agree very well. Figure 1(b) shows the temperature dependence of the contact in a unitary Fermi gas when $1/(k_F a) = 0$ [5]. Also shown in this figure are predictions based on the high temperature virial expansion (dashed lines) and three different strong-coupling theories, which deviate from each other near and below the critical temperature for superfluidity ($\sim 0.2\,T_F$) where T_F is the Fermi temperature [4]. While our data show good broad agreement with the theoretical calculations, we can not yet distinguish between the different calculations with our current experimental uncertainties.

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Quasi Two-Dimensional ^{6}Li Fermi gas

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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 mesoscopic behaviours can also emerge. One example is shell structure which arises due to the filling of discrete shells in the tightly confined transverse direction. This shell structure leads to steps and discontinuities in the evolution of various physical parameters such as the density profile, chemical potential and specific heat [1]. We have studied the crossover from 2D to 3D in a weakly interacting Fermi gas and have seen the emergence of shell structure in the density profiles.

A 2D Fermi gas must satisfy $k_B T, E_F < \hbar\omega_\perp$. We achieve this using a 2D optical trap produced by tightly focusing a circular Gaussian beam in one direction with a cylindrical lens. The trapping frequencies are $\omega_z/2\pi \approx$ 2.8 kHz and $\omega_r/2\pi \approx$ 47 Hz ($\omega_x \approx \omega_y \equiv \omega_r$) in the tight and weakly confined directions, respectively, giving an aspect ratio of $\sim$ 60. For an ideal Fermi gas, $E_F < \hbar\omega_\perp$ for $N \lesssim$ 1800, to achieve the 2D regime.

We have observed reduced dimensionality by studying the evolution of the cloud size versus atom number [2]. Figure 1(a) below shows the root mean square (rms) cloud width in the weakly confined radial (y) direction (main panel) and the tightly confined (z) directions (inset) as a function of atom number N at 992 G ($a = -4300\,a_0$) after 500 μs time of flight. The scaling of the cloud width with atom number is seen to change in both figures showing the signature of the dimensional crossover. The solid and dashed lines are scaled theoretical calculations of the cloud width for a weakly interacting and ideal Fermi gas, respectively. The data points agree very well with the weakly interacting theory. Figure 1(b) shows the aspect ratio $\kappa = \sigma_z/\sigma_y$ of the cloud versus atom number. For a 3D cloud the aspect ratio would be constant for all N; however, the variations we see indicate a clear departure from 3D behaviour. The steps in the gradient of the aspect ratio (inset) correspond to the occupation of new transverse shells, for atom numbers predicted at the location of the arrows. This is the first study of this dimensional crossover and the associated shell structure in a Fermi gas and opens the way to studies of the phase diagram and superfluidity in 2D Fermi gases.

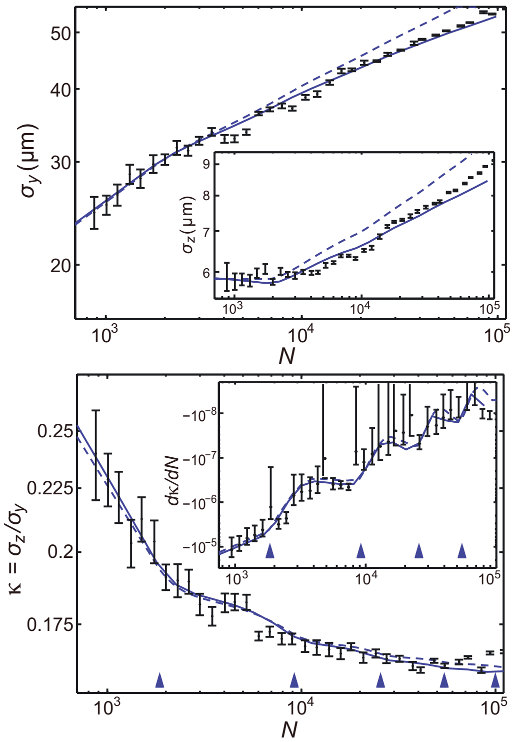

Figure 1: Cloud size (a) and aspect ratio (b) for a weakly interacting Fermi gas in the dimensional crossover from 2D to 3D. Points represent the experimental data and the solid (dashed) line is the theoretical prediction for a weakly interacting (ideal) Fermi gas.

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Exact Quantum Dynamics of Fermionic systems

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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, to validate the potential quantum emulators, or to benchmark approximate approaches, a numerical simulation of the exact real-time dynamics is required.

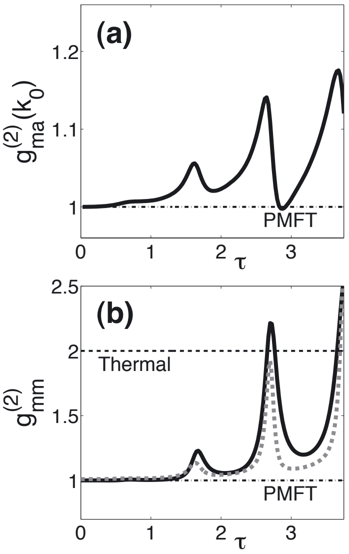

Fig. 1: Dynamical growth of second-order correlations: (a) Atom-molecule and (b) molecule-molecule correlations. Solid lines: exact, phase-space result; dot-dashed lines: pairing mean-field result; thick dashes: approximate semiclassical result.

To this end, we apply the Gaussian phase-space representation for fermions to dynamical simulations of large scale systems. Earlier work focussed on simulations in imaginary time, to determine the ground-state properties of many-body systems. By contrast, we focus on the *real-time* dynamics of many-body quantum systems, a class of problems for which few practical exact methods exist.

For the first application of the fermionic phase-space method to a multimode dynamical problem [1], we consider the dissociation into pairs of correlated fermionic atoms of a uniform 1D molecular BEC initially in a coherent state at zero temperature. Assuming sufficiently low densities, we neglect s-wave scattering interactions to simplify the treatment. We simulate 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 ($d = 2^M n_{\max} \gg 10^{300}$). In regimes where there is large molecular depletion, we see the growth of strong correlations, in contradiction to the approximate mean-field results. We were able to benchmark a semiclassical approach, with number-uncertainty built into the initial conditions, that qualitatively reproduces the large $g^{(2)}_{\rm mm}$ correlations seen in the molecular field (Fig. 1b).

Although we report here only on 1D simulations, we have also implemented 2D and 3D calculations and found that the method works reliably in higher dimensions. We have also explored how different mappings to stochastic equations can dramatically alter the performance of the numerical simulations [2].

In work in progress, the Hubbard model of interacting fermions on a lattice has been implemented and, for small lattices, is being checked against exact number-state calculations. As well as the intrinsic interest of the Hubbard model, this work will allow fermionic models with s-wave scattering to be simulated exactly. It also provides a convenient starting point for introducing a range of efficient approximate approaches that can then be benchmarked.

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Hydrodynamic expansion of a strongly interacting Fermi-Fermi mixture

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We observe two distinct phenomena of hydrodynamic behaviour (inversion of aspect ratio and collective flow) in the expansion of an ultracold Fermi-Fermi mixture [1]. Two species, 75,000 ^{6}Li atoms and 20,000 ^{40}K atoms, are confined in a far-detuned optical dipole trap and evaporatively cooled to degeneracy. Magnetic tuning of *s*-wave interactions allows to realize the strongly interacting regime at the 154.7 G inter-species Feshbach resonance. The optical trap is switched off and the radial and axial widths, σ_r and σ_z, are measured for both species in the time-of-flight expansion. By tuning across the Feshbach resonance (Fig. 1a,b) the aspect ratios, $A_i = \sigma_r^i/\sigma_z^i$, undergo an inversion, clearly demonstrating the main feature of hydrodynamic behaviour. Also the volume parameters, $V_i = (\sigma_r^i)^2\sigma_z^i$, reveal striking features (Fig. 1c,d): while V_{Li} is substantially reduced by the interaction at resonance, V_K clearly shows a significant increase. The dispersive dependence of V_{Li} can be interpreted as the interaction being repulsive (attractive) below (above) resonance. The observed shift may be related to the magnetic field dependence of the interaction energy in the strongly interacting regime. We also observe collective flow of two strongly interacting Fermi species resulting from the hydrodynamic drag effect. In the trap center, the Li atoms spatially overlap with the smaller K cloud and form a hydrodynamic core. After release from the trap the Li atoms stick together with the K atoms at the Feshbach resonance, and the core undergoes a slow collective expansion resulting in the bimodal spatial distribution of the Li atoms. Our observations of the anisotropic expansion and collective flow constitute a first major step to explore the intriguing many-body physics of a strongly interacting Fermi-Fermi mixture.

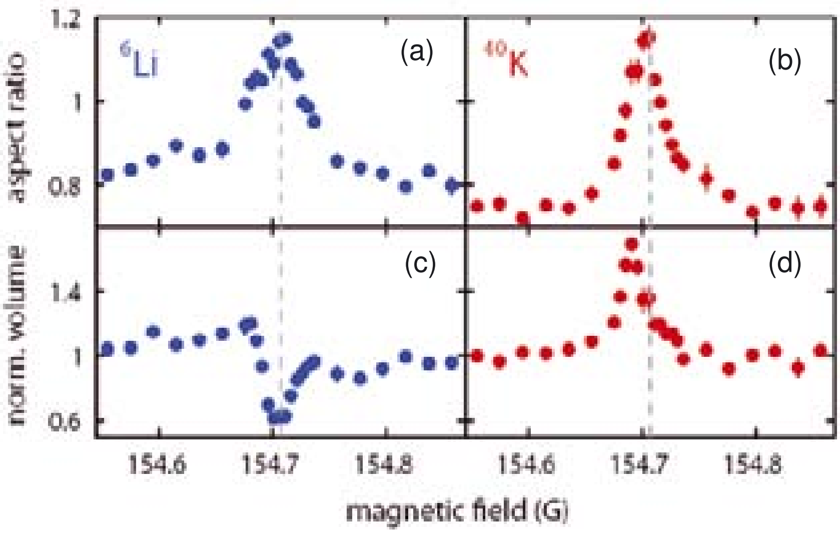

Fig. 1: Magnetic field dependence of the aspect ratios and the volume parameters for ^{6}Li (a,c) and ^{40}K (b,d) observed at the expansion time of 4 ms. The dashed vertical lines indicate the Feshbach resonance.

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Quantum phases in a small-scale Bose-Fermi system

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In recent years, the possibility to address ultracold atoms in single sites of optical lattices and to create mixtures of bosons and fermions drew the attention to the study of small, inhomogeneous systems with complex inter-species interactions [1]. The study of such two- or three-dimensional systems enables understanding of basic physics of more complicated systems, such as interaction-dependent properties of ground states (e.g., frustrations) and the role of symmetry breaking in transitions between different quantum phases. Small, strongly correlated systems may also lend themselves to the process of controlled quantum state preparation and manipulation making it potentially useful in quantum information, quantum-limited measurements, and atomtronics.

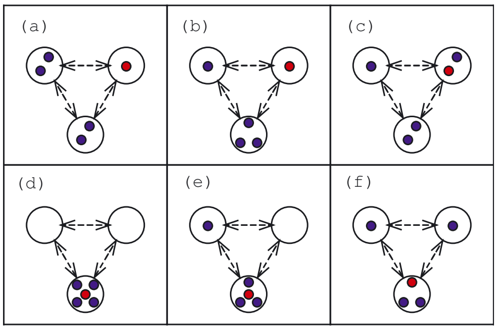

Fig. 1: Schematics of the on-site state configurations of four bosons (blue circles) and one fermion (red circle), contributing to the lowest energy band. The panels (a), (b), (c), and (f) correspond to repulsive inter-species interaction and (d), (e), and (f) to inter-species attraction.

In this work we consider a minimal finite two-dimensional lattice model, namely a three-site ring of a Bose-Fermi ultracold mixture. Such a three-site system may be realized experimentally by engineering magnetic microtraps on an atomic chip, or by combining a harmonic potential with a triangular or Kagome lattice, as suggested in [2]. With the small number of atoms, this system lends itself to the Bose-Fermi-Hubbard model solvable by means of direct diagonalization. We consider the ground state of the system and investigate how the admixture of fermions leads to various phases, depending on the filling factor and inter-species interaction strength.

By examining the tunneling correlations and particle fluctuations in the system, we have found that the system admits mobile and insulating states that are analogous to the superfluid and Mott-insulator states in infinite lattices. The novel insulating states identified in this small-scale system for both commensurate and incommensurate filling of bosons, are purely due to the inter-species interactions, and can be controlled by controlling the interaction strengths and the number of fermions injected into the system. [3]. These unusual insulating phases are connected to the existence of macroscopic self-trapping states in the mean-field regime [4].

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Trapping of Ultracold ^{87}Rb F=1 Atoms in a 10 μm-Period Magnetic Lattice

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Periodic magnetic lattices provide a promising alternative to optical lattices for trapping and manipulating periodic arrays of ultracold atoms and have the potential advantages of no spontaneous emission, low technical noise, low heating rates, highly stable and reproducible potentials, and allowing *in situ* evaporative cooling and RF spectroscopy on the trapped atoms [1-3].

Previously [2], ^{87}Rb atoms in the $|F = 2, m_F = +2\rangle$ ground state were successfully loaded into a 10 μm-period 1D permanent magnetic lattice constructed on an atom chip. Heating due to adiabatic compression in the tight traps and insufficient axial confinement limited the temperature of the trapped atoms to $\sim$ 300 μK and the trap lifetime to $\sim$0.5 s.

We have recently performed experiments for ^{87}Rb atoms optically pumped into the low-field seeking $|F = 1, m_F = -1\rangle$ ground state to reduce three-body recombination, to increase the lifetime of the atoms in the traps and to reach lower temperatures by evaporative cooling in the lattice. F=1 atoms in a Z-wire trap are loaded into a shallow lattice created by the field from the permanent magnetic microstructure and the bias field from a Z-wire current. After evaporative cooling in the Z-wire trap, $\sim 1 \times 10^6$ atoms are transferred into about 100 sites of the magnetic lattice. Further evaporative cooling in the lattice yields $\sim 3 \times 10^5$ atoms at temperatures of $\sim$1.5 μK, which is close to the BEC transition temperature, and with a trap lifetime of $\sim$ 12 s. Under these conditions, and with improved imaging optics, it is now possible, using *in situ* absorption imaging, to spatially resolve the clouds, each consisting of about 3000 ultracold atoms trapped in individual lattice sites $\sim$10 μm below the chip surface in the 10 μm-period magnetic lattice (Fig. 1).

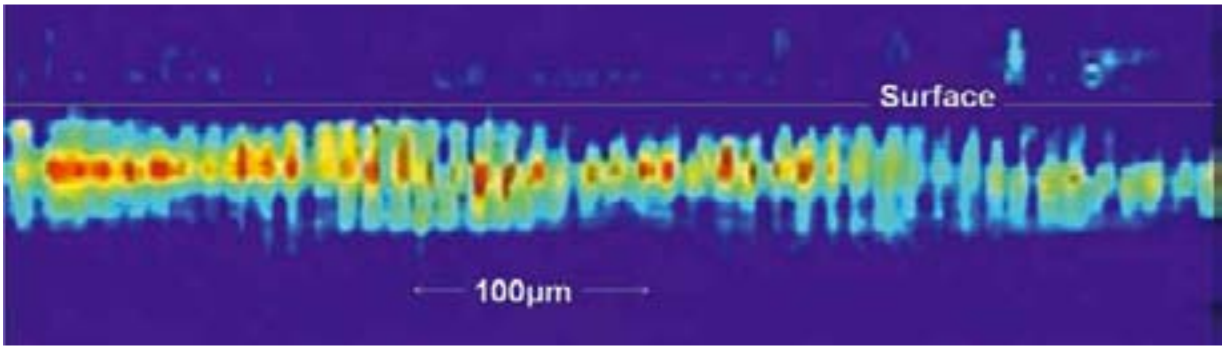

Fig. 1: Fig. 1: Sideview *in situ* absorption image of ^{87}Rb F=1 atoms trapped in a 10 μm-period 1D magnetic lattice. (Pixel size: 3 μm.)

Future experiments include evaporative cooling the trapped atoms to degeneracy to produce multiple BECs in the magnetic lattice, studying decoherence times for a two-component (F=1, F=2) ultracold gas by Ramsey interferometry at distances down to a few microns from the chip surface, and implementing a 2D magnetic lattice [1] with periods down to 1 - 4 μm to perform quantum tunnelling experiments in a magnetic lattice.

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Quantum noise and long coherence time of an interacting Bose-Einstein condensate

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We observe the coherence of an interacting Bose-Einstein condensate (BEC) surviving for an unprecedented time in a trapped Ramsey interferometer [1]. A two-component ^{87}Rb BEC is magnetically trapped on an atom chip in the internal states $|F = 1, \ m_F = -1\rangle$ and $|F = 2, m_F = 1\rangle$ which are coupled via a two-photon MW-RF transition. In the Ramsey sequence (Fig. 1a) the first $\pi/2$ pulse excites collective oscillations of the components. The relative phase initially becomes spatially inhomogeneous but the dynamics in the second half of the cycle reverses this, so that it is again uniform across the condensate. This periodic mean-field driven dephasing and rephasing of the BEC is observed through measurements of the visibility of interferometric fringes (Fig. 1b). We also apply a conventional spin echo technique (Fig. 1c) to reverse the relative phase evolution and compensate for asymmetric losses of the internal states by inverting the populations. Maximum revivals of the visibility are observed (Fig. 1d) if the π pulse is applied at the end of the collective oscillation when the relative phase is uniform along the condensate. The mean-field model correctly predicts the period of the visibility revivals (red dotted lines) but overestimates their magnitudes in both sequences. A truncated Wigner model (black solid and blue dashed lines) [1] is used to account for the dynamical quantum noise, and is in excellent quantitative agreement with our observations. Visibility decay in the spin echo sequence reveals a long coherence time of 2.5 s. We speculate that in our observations coherence is limited by fragmentation of the interacting BEC in addition to quantum phase diffusion.

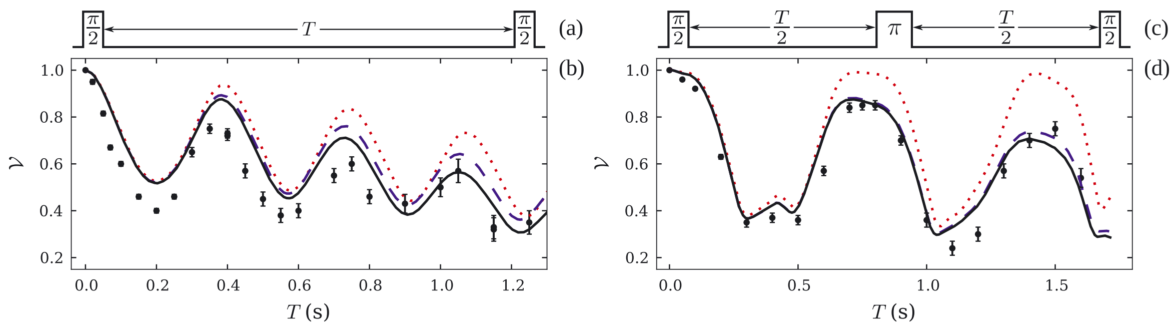

Fig. 1: Measured visibility $\mathcal{V}$ (filled circles) in Ramsey (a) and spin echo (c) sequences as a function of the evolution time T (b, d). Curves correspond to simulations using coupled Gross-Pitaevskii equations (red dotted line), truncated Wigner model without (blue dashed line) and with (black solid line) classical noise.

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High visibility gravimetry with a Bose-Einstein condensate

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A Bose-Einstein condensate (BEC) is frequently described as the matter-wave analog of an optical laser – the preferred source for optical interferometry. In this project, we have demonstrated an atom interferometer-based gravimeter using a ^{87}Rb Bose-condensed source [1]. Our data represent the highest fringe visibility yet achieved in such a device (Fig. 1), for both standard, and large-momentum-transfer (LMT) beamsplitting using Bloch oscillations [2, 3], leading to a precision of 17 ppm. Furthermore, we have shown explicitly that replacing a thermal source with a BEC leads to a significant increase in visibility (Fig. 1).

Our atomic gravimeter uses nth-order Bragg transitions [4] along gravity as the atom-optic beamsplitters and mirrors in a Mach-Zehnder configuration [5, 6]. This leads to an interferometric phase of $\Phi = 2n\,\vec{k}\cdot\vec{g}T^2$, where $\vec{k}$ is the wave vector of the beamsplitter, n an integer, and T is the time between coupling pulses. By scanning Φ one obtains probability fringes $P = \frac{1}{2}(A + V\cos\Phi)$, where we define V as the visibility and A the fringe offset. For small shifts $\Delta\Phi$ one obtains a signal of $\Delta P = Vn\vec{k}\cdot\Delta\vec{g}T^2$ when sitting at mid-fringe. High signal gain thus requires having a high visibility and a large enclosed space-time area ($\propto 2nkT^2$). Both of these parameters can benefit from the use of a BEC due to its very narrow momentum width $\Delta p \ll \hbar k$.

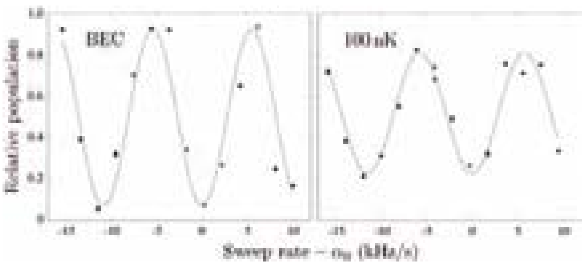

Fig. 1: Fringe comparison of a BEC source and a thermal source, for an $n = 1$, $T = 3$ ms gravimeter.

Comparing a 100 nK thermal atom-cloud with a BEC in our gravimeter under identical conditions, we found that a BEC leads to a significant improvement in visibility from 55% to 85%. A one-dimensional simulation of the interferometer produces no difference in visibility, and we conclude that the lower visibility is the result of technical effects, to which the thermal state is more susceptible. This can be likened to optical interferometry, where laser sources are preferred to white-light sources for practical reasons.

By increasing the enclosed space-time area to $n = 3$ using LMT, we achieve a precision of 17 ppm. Using Bloch-based LMT, a significant improvement in visibility to 24% is observed compared with previous work [3]. Crucially, we found that an imposed number variation of over 300% produced no measurable effect on fringe quality or sensor precision, provided the BEC had reached the ballistic expansion regime; this is in contrast to a common view that BEC is unsuitable for interferometry due to atom-atom interactions. The outcomes of this project suggest that, if combined with state-of-the-art BEC production and interferometer design, BEC sources can provide avenues to increase the best sensitivity realised so far with an atomic gravimeter [6].

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Optically trapped atom interferometry using the clock transition of large ^{87}Rb Bose-Einstein condensates

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We recently produced a Ramsey-type atom interferometer operating with an optically trapped sample of 10^6 Bose-condensed ^{87}Rb atoms. We investigate this interferometer experimentally and theoretically with an eye to the construction of future high precision atomic sensors [1]. Our results indicate that, with further experimental refinements, it will be possible to produce and measure the output of a sub-shot-noise limited, large atom number BEC-based interferometer.

The optical trap allows us to couple the $|F = 1, m_F = 0\rangle \rightarrow |F = 2, m_F = 0\rangle$ clock states using a single photon 6.8 GHz microwave transition, while state selective readout is achieved with absorption imaging. We observe that the $|F = 1, m_F = 0\rangle$ and $|F = 2, m_F = 0\rangle$ states are fully miscible on the timescale of the experiment, in contrast to the magnetic states $|F = 1, m_F = -1\rangle, |F = 2, m_F = 1\rangle$ typically used in chip experiments. We analyse the process of absorption imaging and show that it is possible to observe atom number variance directly, with a signal-to-noise ratio ten times better than the atomic projection noise limit on 10^6 condensate atoms. We discuss the technical and fundamental noise sources that limit our current system, and outline the improvements that can be made.

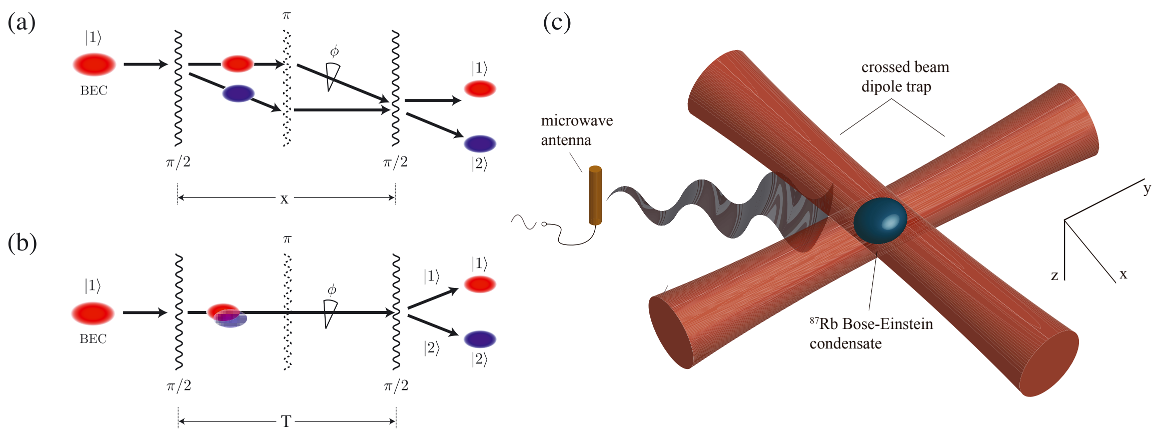

Figure 1: The Ramsey interferometer scheme. An atomic wavepacket is split into two components, allowed to evolve for a time T, and then recombined. The atoms can be coupled to a different internal state, remaining spatially overlapped, or can be coupled to another momentum state, so that the interferometer encloses an area. (a) A spatial Ramsey interferometer is sensitive to inertial effects. (b) The subject of this paper: a temporal Ramsey interferometer is sensitive to state dependent phase shifts. A π pulse allows reflection for the separated beam path interferometer and imposes a ‘spin echo’ effect for the trapped system. (c) The experimental setup. A single photon microwave transition drives internal state transitions in a BEC held in a crossed dipole trap.

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Atom Interferometry below the standard quantum limit

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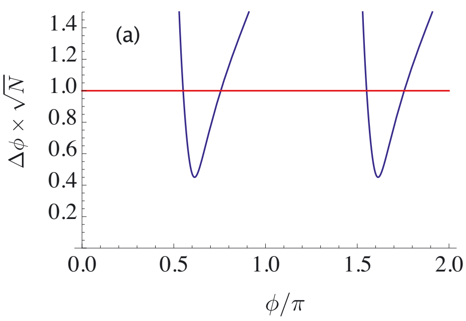
Atom lasers, when used as the source for an atom interferometer, show promise for increased sensitivity of electric, magnetic, and gravitation fields, as well as rotations and accelerations. The use of massive particles over photons offers the possibility of many orders of magnitude increase in the sensitivity 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 2 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.

Recently there have been two experiments demonstrating atom interferometry with sensitivity below the standard quantum limit [2, 3]. Both of these experiments used a double interferometer scheme, where the first interferometer is used to prepare the phase-squeezed state, via nonlinear de-phasing of the relative phase. The second interferometer uses this squeezing to perform a phase measurement with sensitivity which surpasses the standard quantum limit. However, both of these experiments used a small number of atoms (approximately a few thousand), so the absolute sensitivity of the phase measurement is not as precise as for a large number interferometer operating above the standard quantum limit.

We have investigated if it is possible to perform a similar experiment, but with a much larger number of atoms. We found that although the scattering properties of ^{87}Rb aren't favourable for Kerr squeezing experiments, that a 50% enhancement over the standard quantum limit was achievable with 10^6 atoms [4].



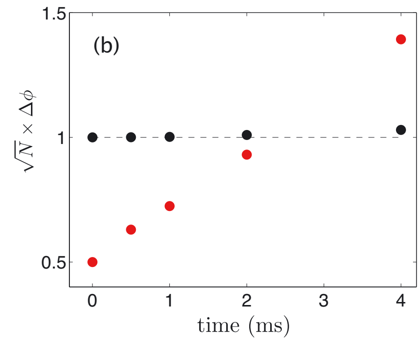


Fig. 1: (a) Phase sensitivity of a large atom number interferometer when Kerr squeezing is employed. (b) Phase sensitivity as a function of hold time of the second interferometer for a squeezed state (red circles) and a uncorrelated state (black circles). The Phase squeezed state de-coheres at a faster rate.

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Interferometry and EPR Entanglement in a BEC

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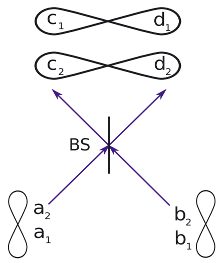
Entanglement is the basis of the EPR paradox, and macroscopic entanglement is a challenging frontier in modern physics [1]. It also has potential applications in sub shot-noise interferometry and ultra-sensitive detection beyond the standard quantum limit. Bose Einstein condensates (BEC) of ultracold atoms are excellent candidates to provide entangled states involving a large number of massive particles, with novel applications. Recent experiments have observed spin-squeezed states in a BEC of ^{87}Rb atoms [2].

We have theoretically shown that entanglement is possible between ground-state BECs with attractive interactions, trapped in two potential wells at nano-Kelvin temperatures, using a modified Hillery-Zubairy non-Hermitian operator product criterion [3]. This is more powerful than the spin-squeezing criterion, as it clearly demonstrates entanglement between the spatially separated two modes. We also show the criterion is a direct indicator of a phase measurement below the standard quantum limit.

In order to extend squeezing measurements to true EPR entanglement at spatially separated sites, a common procedure in optics is using quadrature measurement via phase-sensitive local oscillators. For the two-mode scheme, a BEC local oscillator is not readily obtainable. Experimentally, the two-mode technique requires a phase-sensitive interference of particles from the two wells, which is useful for interferometry, but not for demonstrating true EPR entanglement.



Instead, we propose a dynamical entanglement scheme in which the signature of entanglement comes from spin measurements. We consider four-mode interferometry with two spin orientations in each of two separated potential wells. The BEC is prepared in a phase-coherent state. Then, the inter-well barrier is increased, followed by a microwave Rabi rotation, dynamical evolution in each well, and finally recombination via a modulated inter-well potential barrier and another microwave Rabi rotation. The entanglement witnesses used are spin versions of the Heisenberg-product entanglement criterion. These are closely related to entanglement techniques developed in fiber optics. The schematic diagram of EPR spin entanglement is shown on the right.

In extending such techniques to greater numbers of atoms, for increased precision, it is necessary to consider a multi-mode environment with nonlinear losses. We have shown how to carry out such calculations quantitatively, using a truncated Wigner method. Comparisons with atom interferometry experimental measurements in the SUT atom chip laboratory [4] show excellent agreement between experiment and theory [5]. This provides a highly promising avenue for extending quantum-enhanced measurements into regimes of macroscopic atom numbers. In future, this can be extended to demonstrate the EPR paradox using ultra-cold atomic physics.

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Relative number squeezing in condensate collisions

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We demonstrate sub-Poissonian number differences (or relative number squeezing) in atomic four-wave mixing realised via a collision of two Bose-Einstein condensates (BECs) of metastable helium [1]. The collision between the two BECs produces a scattering halo populated by pairs of atoms of opposing velocities (Fig. 1). By dividing the scattering halo into several symmetric zones, we measure the atom numbers and the relative number fluctuations using a 2D array of time and position resolved atom detectors. We show that the atom number differences for opposing zones have sub-Poissonian noise fluctuations, whereas that of non-opposing zones are well described by shot noise (Fig. 2). The atom pairs produced in a dual-number state are well adapted to sub shot-noise interferometry and studies of Einstein-Podolsky-Rosen-type nonlocality tests.

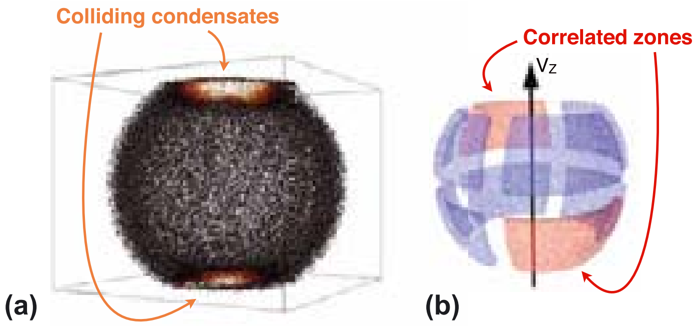
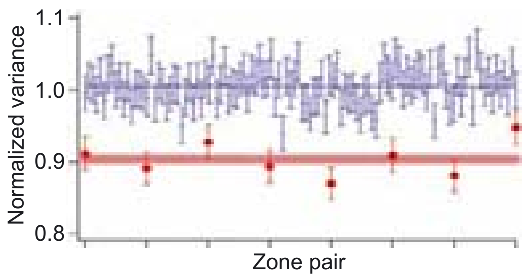


Figure 1. (a) View of the halo of scattered atoms after the collision of two BECs. (b) The analysed part of the halo, divided into $N_z = 8$ zones. An example of two correlated zones is shown (red arrows). The number difference between these two zones have sub shot-noise fluctuations, with the normalised valiance $V < 1$.

Figure 2. Normalised atom number variance of all possible pairs of zones for the halo cut into 16 zones. Circles correspond to the eight correlated zones and crosses to the 112 uncorrelated ones. The observed relative number squeezing in this example is $\sim 10\%$ ($V = 0.9$), which is in agreement with the theoretical calculations using the positive-P representation method, assuming 12% atom detection efficiency.



In an earlier work [2] (see ACQAO Annual Reports for 2009), we have analysed the 3D momentum distribution of scattered atoms and found that the final momenta of atoms lie on an ellipsoid, and not on a perfect sphere as could have been expected from simple momentum and energy conservations. Numerical and analytical calculations agree well with the measurements and explain the ellipticity by a subtle interplay between many-body effects, mean-field interaction, and the anisotropy of the source condensate.

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Superfluidity in dilute gas Bose-Einstein condensates

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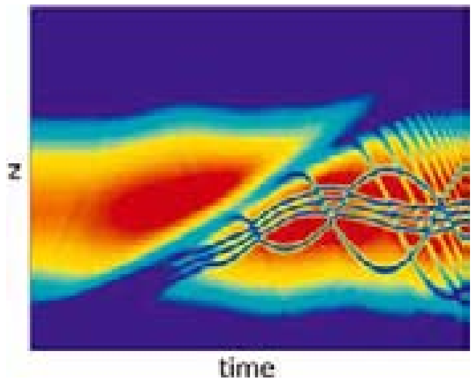
It is generally accepted that dilute gas Bose-Einstein condensates (BECs) in three dimensions are superfluids — they can flow without resistance below a certain critical velocity, and may only rotate by admitting quantised vortices. This project has been investigating a number of aspects of superfluidity in ultra-cold Bose gases in a variety of geometries.

1. A recent experiment by the Engels group at Washington State University has observed evidence for a superfluid critical velocity by dragging both attractive and repulsive obstacles through a harmonically trapped, cigar-shaped BEC [1]. We have modelled these experiments using the 3D Gross-Pitaevskii equation and our results suggest that these experiments do not demonstrate a threshold velocity for the loss of superfluidity [2]. We have also developed a phenomenological model for the energy transferred to a trapped Bose condensate flowing past an obstacle. 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. We have begun work on aspects of superfluid turbulence in trapped Bose-Einstein condensates. In particular, we have attempted to realise the quantum analogue of classical Taylor-Couette flow. This is the name given to a system where a viscous fluid fills a narrow layer between two concentric cylinders rotating independently at constant angular velocity about a common axis. The classical problem has a rich phase diagram with a number of different stable vortex flows intermixed with turbulence. It would be intriguing to compare the quantum phase diagram with that of the classical fluid.

3. We have been working on understanding the relationship between superfluidity, Bose condensation, and the Berezinskii-Kosterlitz-Thouless phase in two-dimensional ultra-cold gases. Prior work has suggested that the BEC phase occurs before the superfluid phase which seems counter-intuitive [3]. However it is difficult to accurately determine the superfluid fraction in a harmonically trapped Bose gas. We have been simulating toroidal systems containing a persistent current at finite temperature, where the observable mass flow gives an accurate measurement of the superfluid fraction. This has lead to interesting questions about the Penrose-Onsager definition of Bose-Einstein condensation in non-equilibrium systems.

4. Our work in collaboration with the the Anderson group at the University of Arizona on the formation of vortex dipoles when an obstacle is dragged through a highly oblate BEC has been published [4].

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C-field simulations of thermal Bose-Einstein condensates

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The aim of this project is 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 provide for non-equilibrium simulations of realistic experimental systems [1].

1. We have developed a 1D model of a continuously pumped atom laser using a stochastic Gross-Pitaevskii equation. In this model the condensate is continuously replenished from a thermal atomic reservoir using a realistic growth model, and the atom laser beam is generated by Raman outcoupling from the centre of the trap. We have identified that atoms leaving the condensate sufficiently slowly can be jostled in a random fashion by thermal fluctuations of the trapped condensate. We have identified this as the cause of significant broadening of the linewidth of the atom laser below a critical outcoupling momentum.

2. An experimental team at the Institut d'Optique has been working on creating a guided atom laser by outcoupling magnetically trapped atoms into a wave-guide formed by a red detuned optical laser. They have been measuring the transmission coefficient as a function of the height of a barrier in the waveguide at finite temperatures in order to make a measurement of the linewidth. We have modeled their system in order to relate their results to the thermal linewidth and to help them refine their experiment.

3. C-field methods for Bose gases have been described as being non-perturbative as they incorporate many-body effects to all orders in the interaction, going beyond the usual factorisation of operator moments in mean-field theories. Using the projected GPE we have quantified the anomalous and non-Gaussian character of the fluctuations of the Bose-field at finite temperature, and demonstrated that the c-field method is consistent with (and goes beyond) symmetry-breaking treatments of BEC at finite temperature [3].

4. We have studied the phases of vortex matter in rapidly rotating two-dimensional Bose-Einstein condensates as a function of temperature. At zero temperature the vortices in the condensate are arranged in a hexagonal lattice, and the temperature is increased, dislocations and disclinations in the lattice start forming in pairs. It is predicted there is a transition from a solid to a hexatic phase when the dislocations unbind, and then to a liquid phase when the disclinations unbind. We have found evidence for this in our numerical simulations.

5. Ongoing work on the microscopic characteristics of vortices in the two-dimensional homogeneous Bose gases was published [4]. This was followed with a study of the temporal statistics of the vortices in this system and a comparison with analytical predictions.

6. Work with University of Queensland BEC group on the formation of condensates by combining a 1D laser sheet with a cigar-shaped BEC was completed and accepted for publication [5].

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Formation of topological defects in Bose-condensed gases

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Quenches of thermodynamic or Hamiltonian parameters in quantum degenerate Bose gases can 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] in order to understand the formation and evolution of the defects [2].

1. Vortices have previously been observed to form in evaporatively cooled Bose-Einstein condensates [3]. Recently we have been simulating condensate formation in highly-oblate traps, and have found that up to ten vortices can be observed in a single condensate, in broad agreement with preliminary experimental results. Our current goal is to try to establish a Kibble-Zurek type scaling of the number of defects with the quench rate for experimentally realistic parameters [2].

2. Quench cooling and condensate formation experiments in prolate trapping potentials at Washington State University have observed what appear to be dark solitons in the resulting condensate images [4]. We have been simulating a one dimensional version of this experiment and have observed the formation of solitons during condensation. We have developed a robust algorithm for the detection of solitons, and can now track their evolution as the system relaxes towards thermal equilibrium [5]. Current data analysis is aimed at establishing if Kibble-Zurek scaling can be observed in this system.

3. We have been studying a quantum Kibble-Zurek scenario in a two-component BEC that is naturally immiscible [6]. 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. By quickly ramping off the coupling, the system returns to an excited 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 with different power-law exponents.

4. Recent experiments in the metastable helium BEC experiment at the Australian National University have observed that the system coherence takes longer to establish than the condensate density. We have been modelling this experiment using the stochastic GPE approach, but so far have yet to be able to reproduce this observation. Further work in this area is aimed at incorporating the non-equilibrium dynamics of the thermal cloud in the description of condensate formation. In particular this may explain some of the features of an earlier experiment at the University of Amsterdam in the hydrodynamic regime [7].

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BEC superpositions in twin wells

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The idea of a macroscopic entity simultaneously existing in two distinct possible states was introduced by Erwin Schrödinger in 1935, as a Gedanken experimental demonstration of the absurdity of quantum mechanics [1]. Since then, evidence has mounted that reality is as absurd as quantum mechanics suggests, with persistent currents (of a few μA) of opposite circulation having been detected in SQUIDS [2]. The fact that Bose-Einstein condensates are mesoscopic quantum entities which can be trapped in tunnel-coupled double wells seems to make them an attractive candidate for the demonstration of mesoscopic superpositions.

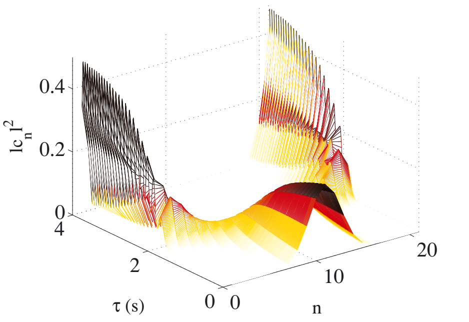

Figure 1: Evolution into a mesoscopic superposition caused by a linear decrease in interaction strength from $U = 1s^{-1}$ to $-3s^{-1}$ in $4s$.

This work investigated methods to manufacture superpositions of two states where all the atoms are localised in one of the wells and investigated how the existence of such a Schrödinger cat state might be proven by realistic measurements [3]. Such states, known as N00N states, promise to be extremely useful in quantum information applications and precision measurement, allowing for a precision beyond the standard quantum limit.

We found that an almost perfect superposition may be possible to make by slowly changing the atomic interactions from positive (repulsive) to negative (attractive). If the process were perfectly adiabatic, the atoms would go from their repulsive ground state, which is a binomial distribution in the two wells, to their attractive ground state, which is a perfect superposition. The development of the occupation probabilities in one of the wells for this process is shown Fig. 1, where we see that the two main probabilities are for either zero or full occupation. As both these exist simultaneously, we have a superposition.

We also investigated how such a superposition could be distinguished from a statistical mixture, investigating various measurement techniques. The standard Ramsay interferometry as used with, for example, two level atoms, only works for a single atom.

We did find a promising candidate in the parity, defined as $P = \sum_n (-1)^n |c_n|^2$, which is an oscillatory function of the accumulated relative phase between the wells while the superposition exists. After creating the superposition, the tunneling (κ) and interaction (U) strengths are set to zero and the system evolves for a time δt with an energy difference δE between the wells. The well symmetry is then restored and tunneling switched on for a time $\pi/4\kappa$. For superpositions, the parity is an oscillatory function of the accumulated phase, whereas for statistical mixtures it always has an expectation value of zero. For the imperfect superpositions which are more likely to be manufactured, the parity remains oscillatory but is a more complicated function.

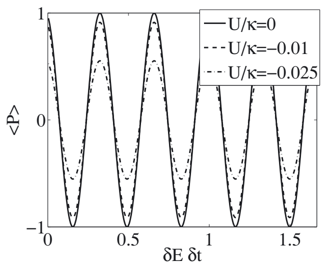

Figure 2: Expectation values of the parity for an ideal superposition, with different ratios of the collisional to the tunnelling interaction strengths.

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Feedback control of an interacting Bose-Einstein condensate

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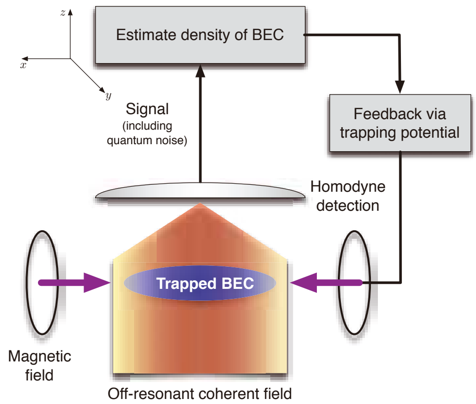

Figure 1: Control setup used to reduce multimode density fluctuations in a BEC

Recently there has been interest in utilising Bose-Einstein condensates (BEC) and atom lasers for precision metrology [1, 2]. However, research has demonstrated that the transverse and longitudinal spatial modes of a BEC exhibit complicated multimode behaviour [3], thereby reducing the precision of atom interferometric measurements. In [4] we theoretically showed that the feedback control scheme shown in Fig. 1 could be used to generate a stable spatial mode for a BEC possessing negligible interatomic interactions. However, many BEC experiments work with condensates that have strong interatomic interactions. Furthermore, it is likely that nonlinear interactions are necessary for the stability of continuously pumped atom lasers [5]. Recently in [6] we further developed the theory presented in [4] to show that feedback control can be used to generate a stable spatial mode for a BEC with a large nonlinearity.

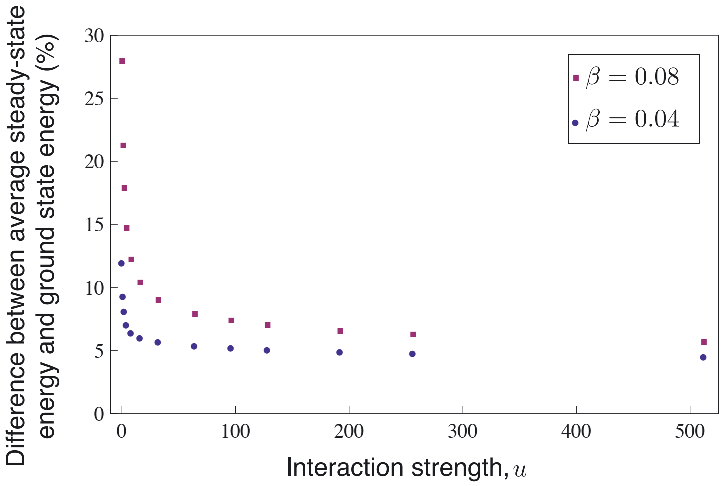

Figure 2: Plot showing how the average steady-state energy compares to the ground state energy as a function of the interaction strength u for (blue dot) $\beta = 0.04$ and (maroon square) $\beta = 0.08$. β is the physical parameter that is related to the strength of the measurement. It is proportional to the intensity of the laser and inversely proportional to the square of the detuning.

In particular, our model solves the problem of inadequacy of the mean-field (coherent state) approximation by utilising a fixed number state approximation. Numerical analysis shows that for optimal values of the feedback control, the average steady-state energy (relative to the ground-state energy) decreases with increasing atomic interaction strength (see Fig. 2). Thus the control scheme is *more* effective for a strongly interacting BEC, which is the case in most BEC laboratories.

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ac-Stark gradient echo memory in cold atoms

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The three-level Gradient Echo Memory has proven to be an efficient, flexible and robust quantum memory candidate. Even with a simple warm vapour cell we have demonstrated recall efficiencies up to 87% [1] and recall of pulses in arbitrary order [2] (See science report by Hosseini et al.). Our experiments to date indicate that we are limited by Doppler effects in our warm atomic gas. The three-level gradient echo system relies on the creation of a linear atomic frequency gradient along the length of the storage ensemble. This is currently achieved using a Zeeman shift induced by magnetic field coils, which have limited flexibility in terms of switching time and spatial precision.

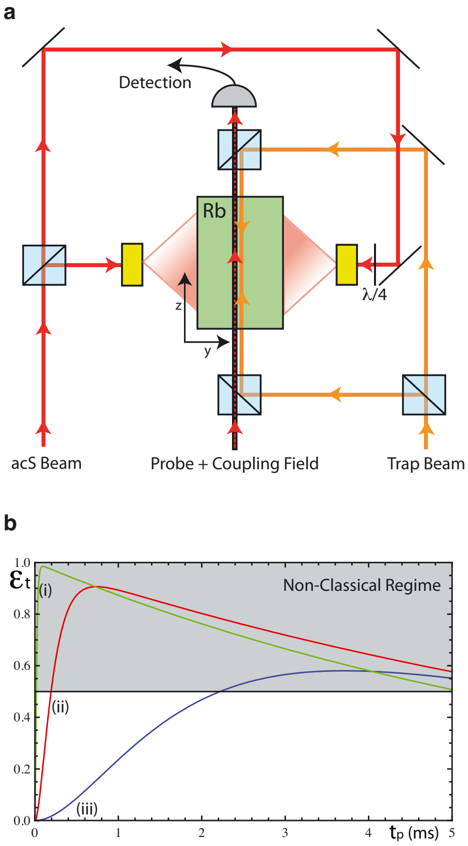

Fig. 1: a) A schematic of the ac-Stark shift system. The atomic frequency gradient is created for atoms held in an optical dipole trap. The Stark beams can be shaped using phase plates or spatial light modulators, or controlled in polarisation by Pockels cells. b) The modelled performance of the system for single pulse storage as a function of pulse length t_p for storage times of one pulse length and different ratios of control beam Rabi frequency to Ramen detuning = (i) 0.01, (ii) 0.003, and (iii) 0.001.

With these limitations in mind we modelled an alternative design for our three-level memory. We considered the use of an ac-Stark shift [3] in conjunction with a cold atomic ensemble in an optical dipole trap. In this system we imagine a laser field with an intensity gradient applied perpendicular to our signal field. The varying intensity of the field will create a varying ac-Stark shift along the length of the ensemble, as indicated in Fig.1(a). We can imagine switching the gradient either by using fields directed from either side of the memory or by switching the polarisation of the ac-Stark beam which, for carefully chosen magnetic levels in the atomic system, can also reverse the frequency gradient. Our modelling showed that, for ^{87}Rb, the best wavelength for the ac-Stark beam is around 810 nm where there is a local minimum in the scattering rate for the F=2, m_F=1 sublevel. While the frequency shift per Watt will vary depending on how the Stark beam is focussed, bandwidths of MHz are quite achievable with less than 10 W of power.

For physically reasonable parameters for dipole optical depth, scattering rates and beam intensities the modelled memory efficiency is shown in Fig.1(b) for different coupling beam powers. The model suggests that high storage efficiency is possible for long times in such a system. We anticipate investigating this system experimentally in the future.

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Efficient gradient echo memory in three-level atoms

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Quantum state storage is an important element in proposals for long distance quantum cryptography networks and quantum computing protocols. Many systems have been proposed in order to realise optical quantum memory. These include electromagnetically induced transparency (EIT), off-resonant Raman interactions, controlled reversible inhomogeneous broadening (CRIB), atomic frequency combs (AFC), and spin-polarization [1].

Our scheme is the Gradient Echo Memory that was developed by groups at the ANU for two-level systems [2, 3, 4]. In our experiments, we have adapted this scheme for three-level atomic ensembles and store light in the long-lived ground states of ^{87}Rb [5, 6]. This works in exactly the same way as the two level scheme, except now the two levels are the ground states of the three-level system. The ground states are coupled by a strong optical field that is far-detuned from resonance with the excited state, as shown in Fig.1(a). Our atomic ensemble is in a warm vapour cell (around 70 degrees) and contains a small amount of krypton buffer gas (0.5 Torr). A schematic diagram of our protocol is shown in Fig.1(b). The essential feature is the atomic frequency gradient that is linear over the length of the cell. After absorption, a pulse of light is recalled as a photon echo by reversing the sign of this gradient. In combination with manipulation of the coupling beam, it is also possible to recall pulses in arbitrary order from the memory [6], as well as manipulate the spectral properties of the echo [4].

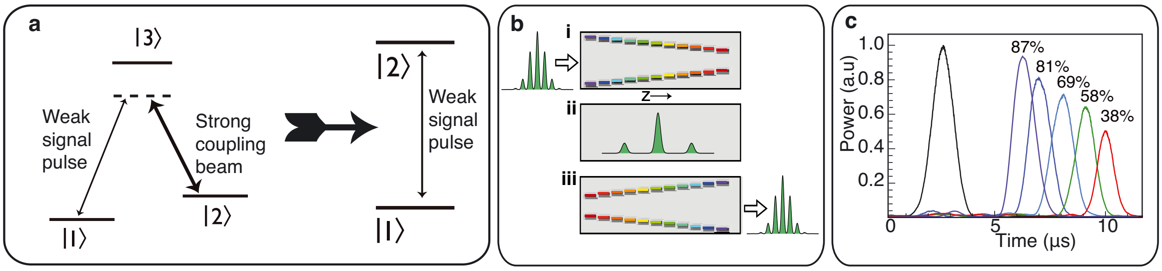

Fig. 1: a) The strong coupling field provides a quasi-two-level system for our memory. b) A pulse of light enters the medium (i) and due to the frequency gradient is decomposed into a Fourier spectrum spatially along the length of the ensemble (ii). After reversing the gradient an echo emerges (iii). c) The recall from our memory as a function of storage time.

The recall from our memory is highly efficient with up to 87% recall for storage times of one pulse-width [7]. This is the highest coherent recall ever measured from a quantum memory candidate. Our experiments suggest that the limitation to our efficiency is the atomic motion and residual scattering due to the strong control field, which is only a few Doppler widths away from resonance with the excited state. These problems may be addressed by using a cold atomic ensemble in, for example, an optical dipole trap.

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Spatial multi-mode quantum networks

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Novel quantum communication and computation protocols require an increasing number of entangled modes. Conventionally, the entangled modes are carried by as many single mode beams [1]. In our work we demonstrate experimentally a way to generate, manipulate and detect multi-mode entanglement within a single beam of light. The scheme, shown in Fig. 1, is based on two optical parametric amplifiers (OPA), one producing squeezed field in a Gaussian mode and the other in a flipped mode. Both beams are superimposed within one optical beam using an optical cavity and their relative phase shift is set to $\pi/2$. Using a multi-pixel homodyne detection [2] we show that this scheme can be used to produce spatial multi-mode entangled states. In particular, the electronic outputs of the multi-pixel detectors are recorded using a fast data acquisition system and various gain functions are applied to data in order to show quantum correlations between a set of spatial modes. In this way, the various quantum networks are implemented into the scheme by using a computer code and processing the collected data. Once an optimal gain functions are found, the scheme operates as a real time spatial quantum network. The great advantage of the scheme is that the whole process of switching between the various quantum networks is fully computer controlled.

First, we coded a basic scheme of a spatial 50/50 beamsplitter. In the language of spatial modes this corresponds to entanglement between two distinct parts of an optical beam; the left and the right part of the Gaussian beam in this case. From the quantum imaging point of view, we demonstrated strong quantum correlations within an optical image. Using the EPR criterion we calculated a value of $\varepsilon = 0.86$ witnessing strong quantum correlations between the two spatial modes. Second, we coded into the scheme a more complex quantum network. In this case, we were able to demonstrate multi-mode GHZ states. In particular, 3-mode and 4-mode GHZ states were produced easily satisfying the GHZ inequalities. Moreover, the scheme can lead to production of cluster states. Currently, a rather low quantum efficiency of the multi-pixel detectors does not allow to explore these quantum states. In conclusion, our scheme allows for fully computer controlled entanglement relationships: there is no need for hardware change to switch from one protocol to another.

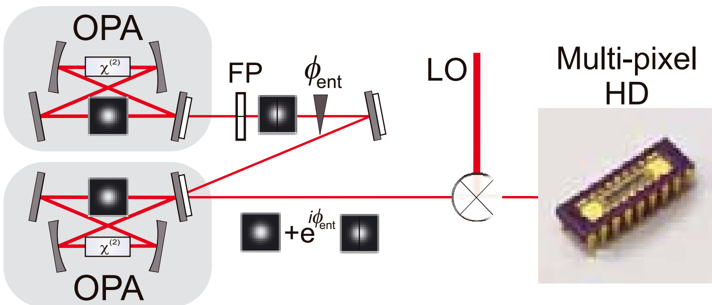

Fig. 1: Overview of the generation and manipulation of entanglement within a single beam of light. FP: flip plate, LO: local oscillator, HD: homodyne detection.

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Spatial reshaping of a squeezed state of light

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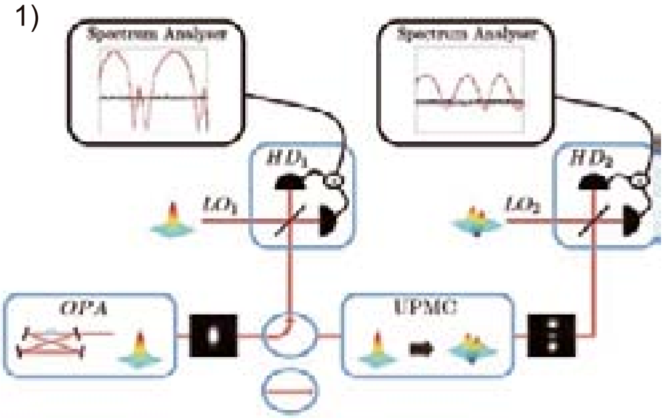
Reshaping the spatial profile, or mode, of a quantum state of light is one of the challenges in many quantum optics applications. We test the noise properties of a universal programmable mode converter (UPMC) [1] and demonstrate that it can reshape the spatial mode of a beam while retaining its quantum properties. No detectable amount of noise is added to the light and only the standard transmission losses through conventional optical elements are found to affect the non-classical nature of the transformed light.

Our results confirm that the UPMC can transform the spatial profile of the light while retaining its quantum properties, excluding passive losses introduced by its optical components [2]. Convincingly, the UPMC does not add noise, and allows for high quality mode matching. It must be noted here that our device is a proof of principle UPMC. A lossless transform is indeed possible given access to higher quality optical components; there is nothing fundamental in the UPMCs design that destroys the quantum state of the light. To that extent, the UPMC is a useful link between the quantum resource and its manipulation. Moreover, the programmable nature of the UPMC makes it a flexible device, allowing for example the same OPA and optical set-up to be used for a wide range quantum enhanced detections.

1)



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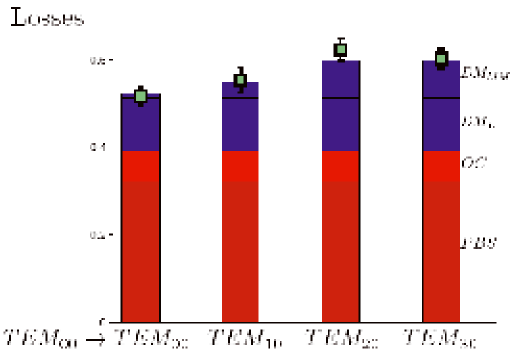

Fig. 1: General schematic of the experiment. The output of the optical parametric amplifier (OPA), a squeezed state in the TEM$_{00}$ mode, is either sent directly to be measured on the first homodyne detection HD$_1$ using a local oscillator in the TEM$_{00}$ mode or sent through the UPMC. The UPMC changes the spatial profile of the light, in this specific example to a TEM$_{20}$. The squeezing levels in the TEM$_{20}$ output mode are then measured using HD$_2$.
Fig. 2: Comparison between the losses calculated from the quantum variance measurements and the losses in power, for different transformations of the spatial profile. PBS shows the losses from the polarizing beamsplitters and OC the losses from the other optical components. DM$_L$ shows the losses from the reflections on the DM and DM$_{MM}$ represents the loss due to the spatial profile mismatch. Finally, the squares represent the losses calculated from the quantum variance measurements.

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Multi-partite qudit entanglement, steering and Bell's nonlocality

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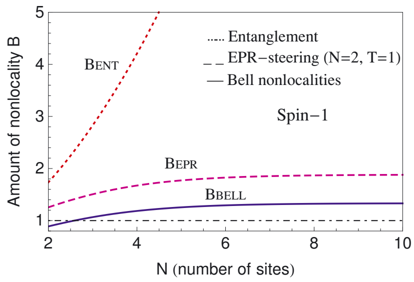
Three forms of quantum nonlocality are entanglement, steering or the Einstein-Podolsky-Rosen paradox, and failure of local hidden variable theories, which we refer to as Bell's nonlocality [1]. We have examined these nonlocalities in situations of largeness, of many sites and many particles (higher dimension). Surprisingly, nonlocality is predicted to persist in all cases, even for mesoscopic quantum systems. Earlier work includes Bell's nonlocality for multisite qubits [2], for bipartite qudits [3], and to a lesser extent on multi-site qudits [4].

We generalise the inequalities of [2] so that they apply to all three nonlocalities, but with a different threshold for each [5]. Our approach can be applied to higher spins. We follow Mermin [2] and Cavalcanti et al [6,7] and construct non-hermitian operators $F_k^{\pm} = (X_k \pm iP_k)/2$ from noncommuting observables X_k and P_k defined for spatially separated sites $k = 1, ..., N$. For any separable or local hidden variable (LHV) model, the inequality $|\langle\prod_{k=1}^{N} F_k^{\pm}\rangle|^2 \leq \int_\lambda d\lambda P(\lambda)\prod_{k=1}^{N}|\langle F_k^{\pm}\rangle_\lambda|^2$ holds. By restricting to local quantum states we can also derive criteria for entanglement. This enables us to obtain a hierarchy of constraints for entanglement, steering and Bell's nonlocality on $|\langle F_k^{\pm}\rangle_\lambda|^2$. We have also shown that entanglement itself is a physical quantity that satisfies conservation laws under certain conditions [8].



Entanglement ($T = N$), steering ($T = 1$) and Bell's nonlocality are predicted when the ratio B of left to right sides of the appropriate inequality (1) is greater than one for N spin-1 systems. Steering relates to the hybrid case introduced by Wiseman et al [1,9], in which some sites are quantum and others not. Such nonlocality is applicable in principle to a spinor BEC with $F = 1$ atoms trapped in an optical lattice.

We derive spin criteria to show entanglement, steering or failure of local hidden variables where $T = N, 1, 0$ respectively [10].

$$|\langle\prod_{k=1}^{N} J_{\pm}^{k}\rangle|^2 > \langle\prod_{i=1}^{T}[(J^i)^2 - (J_z^i)^2 \pm J_Z^A]\prod_{j=T+1}^{N}[(J^j)^2 - (J_z^j)^2]....\rangle \qquad (1)$$

Here the $J_{\pm}^{k}$ are the spin raising and lowering operators for the kth site. The spin j case is applicable to a BEC with many atoms per site. This is also studied for nonmaximally entangled states and shown to allow violation of the Bell and steering nonlocalities for high dimension and large number of sites. Lastly we show how the extent of the violations of the nonlocality inequalities gives information about the number of particles sharing the nonlocality [3].

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Asymmetric Gaussian Steering

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The term "steering" was introduced by Schrödinger in 1935 [1] as a description of the effect which has since become famous as the Einstein-Podolsky-Rosen (EPR) paradox [2]. In 2007 Wiseman *et al.* restated Schrödinger's concept in the language of modern quantum information theory and related it mathematically to the inferred variance criteria used to demonstrate continuous-variable demonstrations of the EPR paradox. In their work, they raised the question of whether a bipartite state could exist where measurements performed on one half could affect the ensemble of possible states describing the other, but not vice-versa.

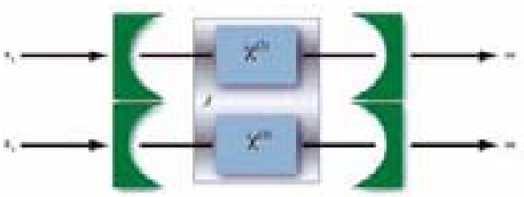

Figure 1: Schematic of the intracavity nonlinear coupler.

For the case of Gaussian measurements, which are normal for continuous-variable states, we answered this question in the affirmative. We showed that there are operating regimes of the intracavity nonlinear coupler where the standard EPR correlations give totally different results for each side, with the paradox being demonstrable by one party but not the other [4]. Measurements of the Duan-Simon criteria can tell us that the system is entangled, as shown in Fig. 2, but do not show this asymmetry.

To show this asymmetric steering, we define the inferred quadrature variances

$$V_{inf}(\hat{X}_i) = V(\hat{X}_i) - \frac{[V(\hat{X}_i,\hat{X}_j)]^2}{V(\hat{X}_j)},$$
$$V_{inf}(\hat{Y}_i) = V(\hat{Y}_i) - \frac{[V(\hat{Y}_i,\hat{Y}_j)]^2}{V(\hat{Y}_j)},$$

with $V_{inf}(\hat{X}_i)V_{inf}(\hat{Y}_i) < 1$ showing that subsystem j can steer subsystem i. In a symmetric system, this would hold with the indices swapped, but for certain parameters we found

$$V_{inf}(\hat{X}_i)V_{inf}(\hat{Y}_i) < 1 \leq V_{inf}(\hat{X}_j)V_{inf}(\hat{Y}_j),$$

which is a demonstration of asymmetric Gaussian steering.

Fig. 2 shows a clear example of this, for the parameters $\gamma_1 = 1$, $\gamma_2 = 36$, $J = 5$, $\Delta_1 = 0.001J$, $\Delta_2 = 200\Delta_1$, $\epsilon_1 = 10^3$, $\epsilon_2 = 80\epsilon_1$, $\chi_1 = 10^{-8}$ and $\chi_2 = 10\chi_1$. The Δ_j and γ_j are respectively the cavity detunings and loss rates. The quadrature angles are $\theta = 9^0$ for EPR$_{12}$ and 130^0 for EPR$_{21}$. We expect that this effect will have applications in quantum cryptography, communications and control. Future work will investigate whether asymmetric steering can exist for all possible measurements, rather than just Gaussian.

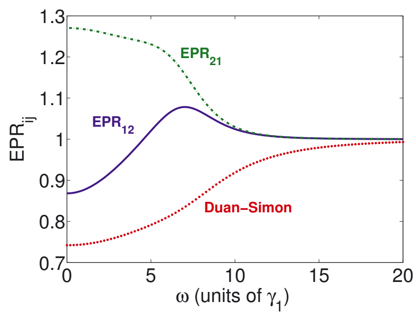

Figure 2: Output EPR and Duan-Simon correlations, showing a clear asymmetry in the EPR measurements.

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Measurement of density fluctuations as a new probe of the physics of quasi-1D Bose gases

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Measurements of atomic correlations and density fluctuations are becoming an increasingly important tool in the studies of ultracold quantum gases. Such measurements are able to probe quantum many-body states of interacting systems, often giving access to key quantities that characterize the system. This is particularly true for one-dimensional (1D) gases, where the effects of fluctuations are enhanced compared to 3D systems and govern the rich underlying physics.

Here we demonstrate that by measuring the density and atom number fluctuations (Fig. 1) in a highly elongated weakly interacting Bose gas we can map out the phase diagram (Fig. 2) of the transition from the ideal gas to a quasi-condensate regime throughout the dimensional crossover from a purely 1D to a 3D regime [1]. We show that the entire transition region and the dimensional crossover are described surprisingly well by the modified Yang-Yang model introduced in Ref. [2]. Furthermore, we find that at low temperatures the linear density at the quasi-condensate transition scales according to an interaction-driven scenario of a longitudinally uniform 1D Bose gas (n_t), whereas at high temperatures it scales according to the degeneracy-driven critical scenario of transverse condensation ($n_\perp$) of a 3D ideal gas.

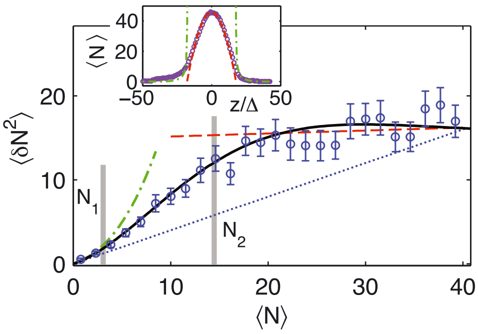

Figure 1. Atom number fluctuations $\langle \delta N^2 \rangle$ versus the mean $\langle N \rangle$ in a quasi-1D Bose gas: solid line – modified Yang-Yang model; dash-dotted – ideal Bose gas; dashed – quasi-condensate; dots – classical ideal gas. The positions of $\langle N_1 \rangle$ and $\langle N_2 \rangle$ correspond to 20% departures from the ideal gas and quasi-condensate regimes, respectively.

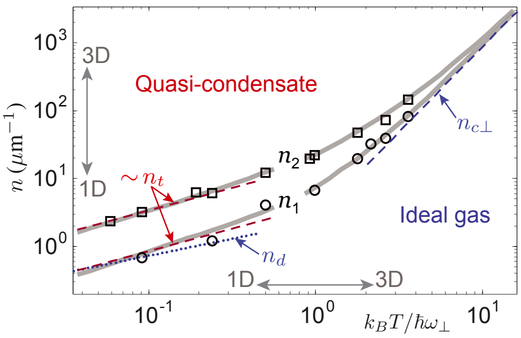

Figure 2. Phase diagram of different regimes in a uniform 1D Bose gas. The experimental data (circles and squares) are in excellent agreement with the modified Yang-Yang model (solid lines) for the linear densities $n_{1,2} = \langle N_{1,2} \rangle / \Delta$, where Δ is the length of a uniform segment in the gas.

In addition, we have measured the third moment $\langle \delta N^3 \rangle$ of atom number fluctuations in a quasi-1D Bose gas [3], which characterises the skewness of the atom number distribution. The skewness is linked to the third-order correlation function $g^{(3)}$, and our measurements demonstrate the presence of true three-body correlations in the gas. Apart from this, we show that the measured third moment is related to a thermodynamic relation that involves a second-order derivative of the equation of state of the gas, and therefore the technique can be used as a sensitive probe of the thermodynamics of a quantum gas.

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Momentum distribution of a weakly interacting quasi-1D Bose gas

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In this work we study the finite temperature behavior of the weakly interacting quasi-1D Bose gas. This system exhibits a crossover between nearly ideal gas and a quasi-condensate regime, which is characterised by the presence of both density and phase fluctuations. Experiments in this regime were recently reported by van Amerongen *et al.* [1] and provided the first quantitative test of the Yang-Yang thermodynamic formalism [2] (also known as thermodynamic Bethe ansatz) using the measured position density profiles. Those experiments also measured the momentum distribution using a novel focussing technique, however, these measurements were not explained theoretically as the construction of the momentum distribution using the known Bethe ansatz and the Yang-Yang thermodynamic formalism is a challenging problem yet to be solved.

In this work we develop alternative theoretical techniques to describe the momentum distribution of a quasi-1D Bose gas in a harmonic trap [3]. We show that (*i*) the width w of the momentum distribution can be determined generally using the Yang-Yang thermodynamic formalism by calculating the kinetic energy per particle $E_{\rm kin}/N = \hbar^2 w^2/2m$ (see Fig. 1), and that (*ii*) the Stochastic Gross-Pitaevskii Equation (SGPE) provides a full description of the momentum distribution in the weakly interacting limit (Fig. 2). Using these theories we provide the first quantitative description of the momentum distribution measurements presented in [1].

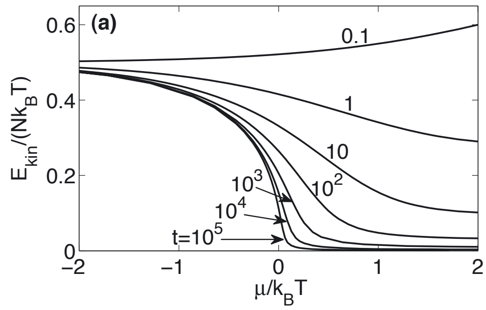

Figure 1. Kinetic energy per particle of a purely 1D uniform Bose gas as a function of the chemical potential μ (all in units of k_BT), for different values of the dimensionless temperature parameter $t = 2k_BT\hbar^2/mg^2$, where g is the 1D coupling constant.

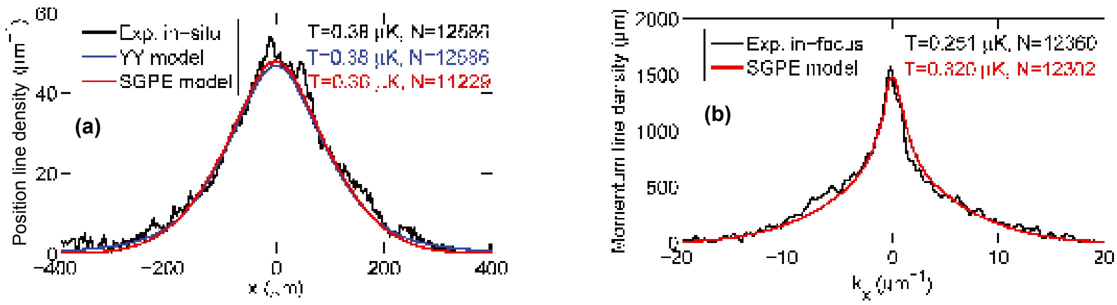

Figure 2. (a) Position-space density profiles from the Yang-Yang thermodynamic formalism (blue), SGPE approach (red), and the experiment (black). (b) Momentum distribution from the SGPE approach (red) and the experiment (black).

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Enhancement of frequency up-conversion in atomic media

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Low-intensity nonlinearity of atomic media associated with light-induced atomic coherence may result in the generation of new optical fields with substantial frequency up-conversion [1]. Our investigations of frequency up-conversion are mainly motivated by possible applications in the generation of correlated fields with a substantial frequency difference; however, an extension of this approach for sensitive atom detection seems realistic.

We have studied frequency up-conversion of near-IR resonant laser radiation in Rb vapour. After excitation into the $5D_{5/2}$ level by co-propagating laser beams at 780 nm and 776 nm, Rb atoms decay to the $6P_{3/2}$ level and then to the ground state, emitting spontaneous photons at 420 nm. At sufficiently high atomic density and laser intensity, blue light with very low divergence appears as a result of wave mixing of the laser fields with the third field at 5.2 μm produced by stimulated emission from the $5D_{5/2} - 6P_{3/2}$ transition. We find that the direction of the coherent blue light (CBL) agrees with the phase-matching relation determined by the wave vectors of all the optical fields and the refractive indices they see. The direction along which optimal matching condition is achieved forms a light-induced waveguide for CBL generation.

The spatial and spectral properties of CBL are very sensitive to various parameters, such as the frequency detuning, the polarization of the applied laser fields and their spatial overlap [2]. We have also studied the influence of optical pumping on CBL generation. Velocity selective optical pumping produced by a laser tuned to the D1 line at 795 nm can decrease the atomic density threshold of CBL generation, enhance the CBL intensity as shown in Fig. 1, and affect the blue beam transverse spatial distribution. Fig. 1c shows (i) CBL temporal dependence when a sharp-edge optical pumping pulse (ii) is applied. We note also that velocity selective depopulation produced on the D1 line may decrease the CBL intensity. Thus, optical pumping allows efficient control of the CBL generation.

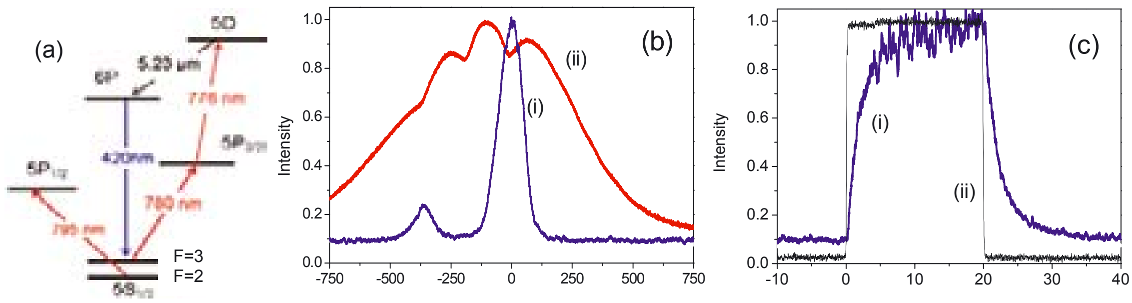

Fig. 1: (a) Energy level scheme; (b) Curve (i) shows the blue light intensity as a function of the optical pumping laser detuning from the $5S_{1/2}(F=2) - 5P_{1/2}(F'=3)$ transition, while curve (ii) represents the reference fluorescence profile; (c) Temporal blue light intensity evolution with pulsed optical pumping.

Possible schemes for generation of ultraviolet and THz radiation, as well as a pair of correlated optical fields from different spectral regions using this approach are under our investigation.

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Relative Phase States

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Studies of phase dependent phenomena in both Bose-Einstein condensates and quantum optics are hindered because phase has at least three different meanings [1]. The introduction of phase as eigenvalues of a linear Hermitian phase operator is the most objective approach [1], and such an operator can be defined for BEC following the method of Pegg and Barnett [2] for EM fields.

For the case of a two mode BEC with mode annihilation operators $\widehat{a}$, $\widehat{b}$ and spatial mode functions $\phi_a(\mathbf{r})$, $\phi_b(\mathbf{r})$ basis states $|n_a\rangle$, $|n_b\rangle$ involving n_a, n_b bosons in the modes can be used to define relative phase eigenstates $|\theta_p\rangle$ for the $N = n_a + n_b$ boson system, where $\theta_p = p(2\pi/(N+1))$, $p = -N/2, -N/2+1, .., +N/2$ is a quasi-continuum of $N+1$ equispaced phase eigenvalues, and from which the Hermitian relative phase operator $\widehat{\Theta}$ is then defined. We have

$$|\theta_p\rangle = \frac{1}{\sqrt{N+1}} \sum_{k=-N/2}^{N/2} \exp(ik\theta_p) \, |N/2-k\rangle_a \, |N/2+k\rangle_b \qquad \widehat{\Theta} = \sum_p \theta_p \, |\theta_p\rangle \, \langle\theta_p| \tag{1}$$

The relative phase eigenstate has several interesting properties. Firstly, it is a state with maximal mode *entanglement* [3] for the a, b sub-systems, so is of interest in quantum information Secondly, it is a *fragmented* state [4], since there are two natural orbitals with macroscopic occupancy. For large N the natural orbitals obtained from the first order quantum correlation function are $\chi_{\pm}(\mathbf{r}) = (\exp(i\theta_p/2)\phi_a^*(\mathbf{r}) \pm \exp(-i\theta_p/2)\phi_b^*(\mathbf{r}))/\sqrt{2}$, with occupancies $(\frac{1}{2} \pm \frac{\pi}{8})N$. For fragmented states generalized mean field theories [5] are required . Thirdly, the relative phase eigenstate is a *spin squeezed* state. Spin operators along $(\widehat{J}_z)$ and perpendicular $(\widehat{J}_x, \widehat{J}_y)$ to the Bloch vector may be defined by $\widehat{J}_x = \widehat{S}_z$, $\widehat{J}_y = \widehat{S}_x \sin\theta_p + \widehat{S}_y \cos\theta_p$, $\widehat{J}_z = \widehat{S}_x \cos\theta_p - \widehat{S}_y \sin\theta_p$, where $\widehat{S}_x = (\widehat{b}^\dagger\widehat{a} + \widehat{a}^\dagger\widehat{b})/2$, $\widehat{S}_y = (\widehat{b}^\dagger\widehat{a} - \widehat{a}^\dagger\widehat{b})/2i$, $\widehat{S}_z = (\widehat{b}^\dagger\widehat{b} - \widehat{a}^\dagger\widehat{a})/2$ are the usual Schwinger operators. For large N the Bloch vector is $\langle \widehat{J}_x \rangle = 0$, $\langle \widehat{J}_y \rangle = 0$, $\langle \widehat{J}_z \rangle = \frac{\pi}{8}N \approx 0.392N$, which is in the equatorial plane with azimuthal angle $\phi = 2\pi - \theta_p$, and inside the Bloch sphere of radius $N/2$ - another indicator of fragmentation. For large N the fluctuations $(\delta\widehat{\Omega}^2 \equiv \langle (\widehat{\Omega} - \langle \widehat{\Omega} \rangle)^2 \rangle)$ in the Bloch vector components are found to be $\delta\widehat{J}_x \approx \sqrt{1/12}N \approx 0.289N$, $\delta\widehat{J}_y \approx 1.30$, $\delta\widehat{J}_z \approx \sqrt{(1/6 - \pi^2/64)}N \approx 0.112N$. As $|\langle \widehat{J}_z \rangle|/2 \approx 0.196N$ we see that $\delta\widehat{J}_x \cdot \delta\widehat{J}_y \approx 0.375N$ is greater than $|\langle \widehat{J}_z \rangle|/2$, consistent with the Heisenberg uncertainty principle. However, although $\widehat{J}_x$ is unsqueezed, the other perpendicular component $\widehat{J}_y$ is highly squeezed, with a fractional fluctuation $\delta\widehat{J}_y / \langle \widehat{J}_z \rangle$ of order $1/N$. The relative phase state could be of interest in Heisenberg limited interferometry [6].

Finally, even though no proposal yet exists for preparing a BEC in a relative phase eigenstate, relative phase eigenstates are a valuable theoretical concept for describing behaviour in BEC interferometry experiments, such as the Dunningham and Burnett [7] proposal for Heisenberg limited interferometry in two mode BEC.

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Self-guiding of matter waves in optical lattices

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Optical lattices have proven to be a powerful tool for the manipulation of BECs, and for uncovering new effects in the coherent matter wave due to the interplay of periodicity and nonlinearity. This work demonstrates three new results on the nature of BECs in the lattice: (1) that self-induced waveguide structures are possible in the lattice; (2) that these waveguides may support continuous or pulsed atom flow; (3) that waveguide localisation may be achieved, and spontaneous flow may emerge, as an initially deep lattice is reduced in depth [1].

Earlier work carried out within ACQAO demonstrated that the ground state nonlinear Bloch wave may be truncated and localised by Bragg reflection within the linear band gaps of an optical lattice [2] (see Fig. 1(a,b)). Extending this work to lay the foundation for possible applications of matter wave control in two-dimensional lattices, it is found that states with complex geometries, and even high aspect ratios like waveguides with flow (see Fig. 1(c)) may be truncated and are stable, provided the lattice is sufficiently deep (here found to be six recoil energies and deeper). States with flow are found to be stable provided the phase change between neighbouring sites does not exceed $\pi/2$. Single site waveguides are found to support the propagation of solitonic density pulses (see Fig. 1(d)), which propagate without change of shape (even around sharp corners), and pass through each other without dependence on phase.

A possible scheme for generation of waveguides with and without flow is to begin with a deep lattice and use single-site addressability techniques [3] to obtain the geometry of interest. Initially the phase will be random between sites (see Fig. 1(e), left panels), but gradually reducing the depth of the lattice will lead to the development of phase coherence and the possibility of spontaneous flow through the Kibble-Zurek mechanism (see Fig. 1(e), right panels).

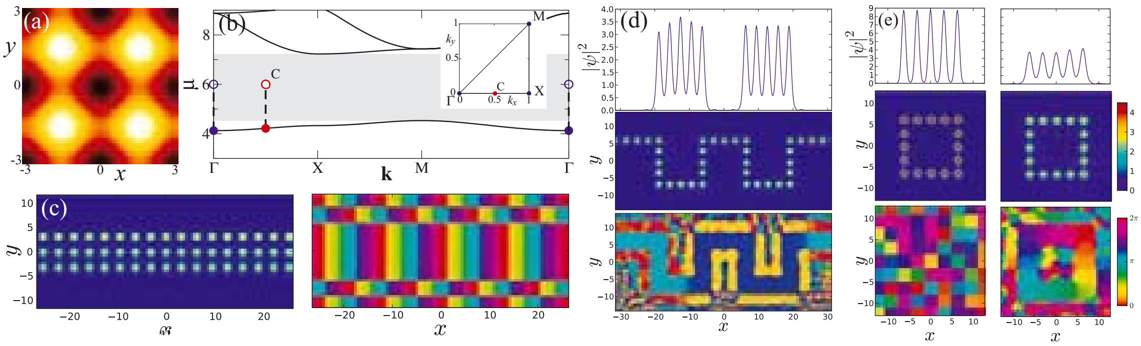

Fig. 1: (a) Intensity plot of optical lattice. (b) Band diagram including position of linear (solid circles) and nonlinear (open circles) Bloch waves showing shift of chemical potential into linear gap where truncation can occur. Inset: the associated Brillouin zone, with high symmetry points Γ, X and M. (c) State with nonzero $\mathbf{k}$ marked as C in (b) (left: density, right:phase). (d) Single site waveguide with bends supporting solitonic pulse propagation and (e) generation of a toroidal flow (right panels) from an initially random phase state (left panels) through the Kibble-Zurek mechanism. Color bars on the right show density (top) and phase (bottom) values for associated panels in (d,e). Top panels: cut through density profile. In all cases the lattice depth is $V_0 = 6$ in units of lattice recoil energy.

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Controlled transport of matter waves in driven optical lattices

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The idea of controlled manipulation of stable, spatially localized matter-wavepackets is attractive from the point of view of the developing atomic interferometry and precise measurement techniques based on the use of the Bose-Einstein condensates (BECs). In the recent years optical lattices were suggested as a means of achieving controlled transport of matter waves. In particular, theoretical studies of nonlinearly localized matter-wave solitons, loaded into a rapidly driven one-dimensional (1D) asymmetric optical lattice potential, have demonstrated that such an "optical ratchet" does not jeopardize the dynamical stability of the solitons and enables their mass-dependent transport [1, 2].

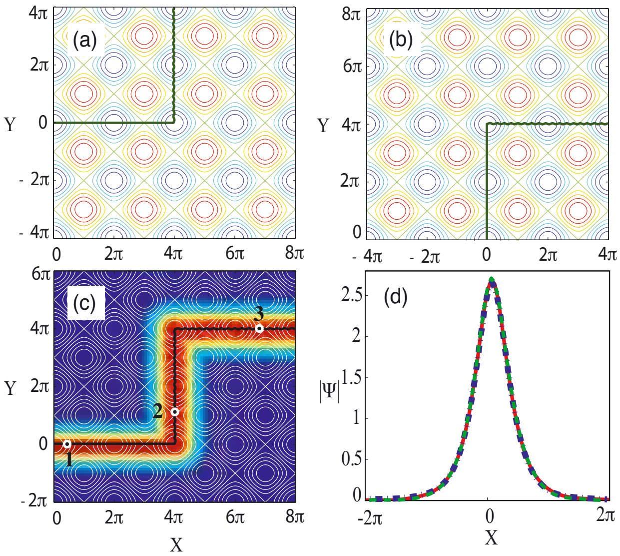

Figure 1: (a,b) Center of mass trajectory of a moving soliton in a rocking lattice potential, superimposed onto the contour plot of the potential at the initial time moment, and, in (c), onto the density profile of the moving soliton. Sharp turning points correspond to the switching of the directed mobility channels effectively created by driving. (d) The profiles of the moving soliton corresponding to the points 1 (solid), 2 (dashed), and 3 (dash-dotted) in (c).

Creation and transport of matter-wave solitons in a 2D or 3D trapping geometry is a more complex and challenging task, especially considering the instability of the condensate with the negative scattering length. Different methods of stabilization were suggested, many of them relying on the time-periodic management of the scattering length, or non-local interaction between ultracold atoms. Furthermore, various theoretical studies have established that stability of the nonlinear localized matter-wave can be greatly improved in an optical lattice, even in the case when the dimensionality of the soliton and the lattice do not coincide. However, an optical lattice potential may greatly inhibit the mobility of the localized states, and the main challenge is to suggest an efficient method for non-destructive, dynamically controlled transport of the stabilized wavepackets.

Here we present the theory of nonlinear dynamics, controlled transport, and "routing" of 2D matter-wave solitons, created in a BEC with a negative scattering length, by means of a driven "rocking" 2D optical lattice. This type of a dynamically reconfigurable lattice has been recently realized in experiments with ultracold atoms [3]. Our numerical analysis, based on the mean-field Gross-Pitaevskii model, and the theory based on the time-averaging approach, demonstrate that a fast time-periodic rocking of the 2D optical lattice enables efficient stabilization and manipulation of nonlinear localized matter wavepackets along dynamically created "mobility channels", as shown in Fig. 1 [4].

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Quadripartite CV entanglement and cluster states

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This work is a continuation of research into multipartite continuous variable entanglement, where ACQAO and the Jack Dodd Centre have provided theoretical support for the quantum optics experiments undertaken at the University of Virginia.

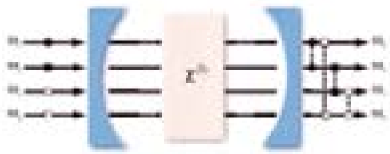

Figure 1: Schematic of the $\chi^{(2)}$ crystal inside a pumped cavity. The inputs are on the left and the output downconverted modes on the right.

Olivier Pfister is able to use intracavity systems which produce quadruply concurrent downconversion. With four pump lasers, as shown in Fig. 1, this results in four downconverted output modes which are inseparable [1] and will find many uses in quantum information technologies. The system as shown in Fig. 2, with only two pumps, provides a continuous variable cluster state in the limit of strong squeezing, which is a proposed resource for one-way quantum computing, but may also be useful for more viable tasks.

To demonstrate the existence of quadripartite entanglement, where none of the four output subsystems may be described separately from the others, we calculated an optimised form of the van Loock-Furusawa correlations [3], finding that both systems we considered exhibited entanglement for a wide range of parameters, both above and below threshold. The four-pump scheme showed almost complete violation of the inequalities around the oscillation threshold when all the nonlinearities were equal and, more importantly for experimental realisations, still exhibited genuine inseparability with differences among the interaction strengths. An important advantage of this scheme is that the entanglement is present well above threshold, where the outputs are of truly macroscopic intensity.

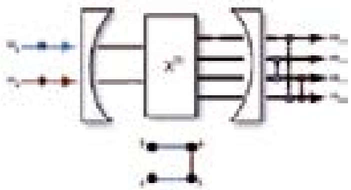

Figure 2: Schematic of the cluster state system and graph state representation of the outputs.

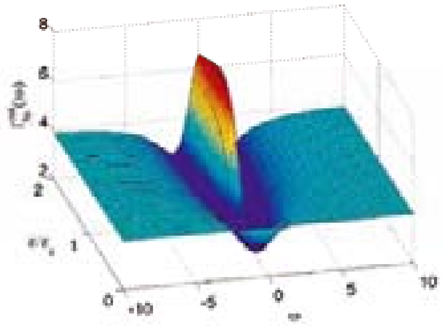

Figure 3: Output spectral correlation for the cluster scheme. A value of less than one signifies entanglement.

The cluster state also provided entanglement both above and below threshold, with a small injected coherent signal necessary above threshold to prevent phase diffusion. There are three inequalities which must all be violated to demonstrate full inseparability, with one of them being shown in Fig. 3. The other two are equal to each other, but different from I_{56} for the same parameters. This is unlike the four pump system, where for equal parameters the spectra are identical and no injected signal is required. We found that both schemes are potential sources of bright entangled states and that the usefulness of the two-pump scheme as a cluster state will depend on whether less than perfect squeezing is acceptable.

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Production of entanglement in Raman three-level systems using feedback

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The production and manipulation of entangled states has been a major feature of quantum information research in the last several years. The efforts in this direction were rewarded with extraordinary experimental advances that led to the realisation of entangled states in a variety of physical systems, including entanglement involving multiple particles and long-lived entangled states. A promising approach to deal with the problem of decoherence is the use of active quantum feedback control. In fact, quantum feedback has been recently proposed and used to improve entanglement production and stability in both continuous and discrete variable systems.

Recent work by Carvalho and Hope [1] has uncovered a direct feedback scheme that, under an appropriate detection strategy leads, to the production of highly entangled states of two atoms or ions in a cavity. Motivated by the perspective of experimental implementations, and the possibility of improving the proposed scheme even further, we analysed the use of Raman transitions in place of the optical dipole transitions to reduce the rate of decoherence due to spontaneous emission. We also characterised the decoherence effect of other imperfections; delocalisation of the trapped ions, and inefficiency in the detection apparatus.

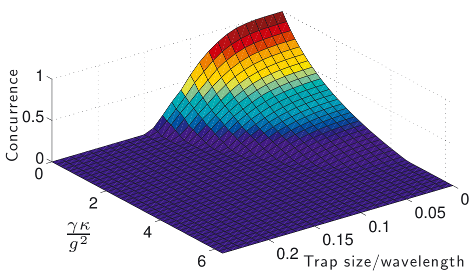

Fig. 1: Steady state concurrence of the two atom system as a function of the ion delocalisation and the spontaneous emission rate. The x axis is a measure of the standard deviation of the particles as a fraction of the cavity mode wavelength λ. The y axis is the total spontaneous emission γ rate as a fraction of g. The z axis is the steady state concurrence. The detector efficiency is 50%.

We found that, although the Raman transitions slow down the decoherence, they also slow down the feedback process, and these two effects cancel out. While this doesn't help with reducing the effect of decoherence it does help with some practical implementation issues. The use of Raman transitions slows down all important rates in the system, which means that the rate at which feedback pulses need to be applied is reduced.

We also found that a reduced efficiency detector greatly reduces the range of the other parameters (ion localisation and spontaneous emission rate) that allow a highly entangled state to be produced, though the allowable parameters are reasonably within modern experimental capabilities.

The manuscript describing these results is currently in the production stage at Eur. Phys. J. D, and can be found in [2].

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* High impact article

BOOK CHAPTERS

76. A. Sidorov and P. Hannaford, *'From magnetic mirrors to atom chips'*, Atom Chips (Eds. J. Reichel and V. Vuletic), Wiley-VCH (2011), Chapter 1

77. A. Akulshin, R. McLean, A. Sidorov and P. Hannaford, *'Electromagnetically induced absorption and transparency due to long lived Zeeman coherence.'*, New Trends in Quantum Coherence and Nonlinear Optics (Horizons in World Physics, Volume 263), Chapter 1

REFEREED CONFERENCE PROCEEDINGS

78. P.D. Drummond, H. Hu and X.-J. Liu, *'First-principles many-body theory for ultra-cold atoms'*, AIP Conf. Proc. 1246, 55 (2010)

79. E. Kuhnle, P. Dyke, S. Hoinka, M. Mark, H. Hu, X-J, Liu, P. Drummond, P. Hannaford and C. Vale, *'Universal structure of a strongly interacting Fermi Gas'*, Journal of Physics Conference Series 264, 012013 (2011)

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 provided 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 of these categories.

ACQAO has achieved all the original research goals stated in 2002 and again in 2007 for the extension of our Centre. The results are shown in our publications [p.57] and are summarised in the list of research highlights [p.6–15]. They were reported in the leading journals and conferences. Our work has high impact as can be seen by the impressive number of citations [see p.60, KPM's].

ACQAO has provided a creative environment where researchers can focus on research, and have exemplary laboratory and office facilities. The Centre has created enhanced opportunities to meet other excellent researchers within Australia and throughout the world. The Centre provides PhD training of the highest calibre and has supported many outstanding young scientists who now contribute 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

Ben Buchler, Elena Ostrovskaya and Andrew Truscott appointed new long-term staff members at ANU

Chris Vale and Brenton Hall both appointed new long-term staff members at SUT

Ping Koy Lam appointed as Professor and Future Fellow at ANU

John Close and Ken Baldwin appointed Professors at ANU

Nick Robins (ANU) and Hui Hu (SUT) appointed QEII Fellows

Craig Savage (ANU) appointed Professor in 2010

Elena Ostrovskaya (ANU) and Xiaji Liu (SUT) awarded Australian Research Fellow

Karen Kheruntsyan (UQ), Murry Olsen (UQ) along with Andrew Truscott (ANU) and Ben Buchler (ANU) awarded Future Fellowships

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

Joe Hope appointed a continuing position as Reader at ANU

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

Peter Drummnd (UQ and SUT) appointed Australian Professorial Fellow

Qiongyi He (UQ and SUT) and Chris Ticknor (SUT) appointed Australian Postdoctoral Fellows

Students

Warwick Bowen (2003 ANU PhD), Lecturer at UQ

Piotr Deuar (2004 UQ PhD), Marie-Curie Fellowship at Universite Paris-Sud 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), Stanford then UQ in 2009

Gabriel Hetet (2008 ANU PhD), University of Innsbruck

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

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

G. Veeravalli (2009 SUT PhD), Postdoc at Heidelberg with Alexander von Humboldt Fellowship

Angela White (2009 UQ PhD), Postdoc at University of Queensland and previously Newcastle, UK

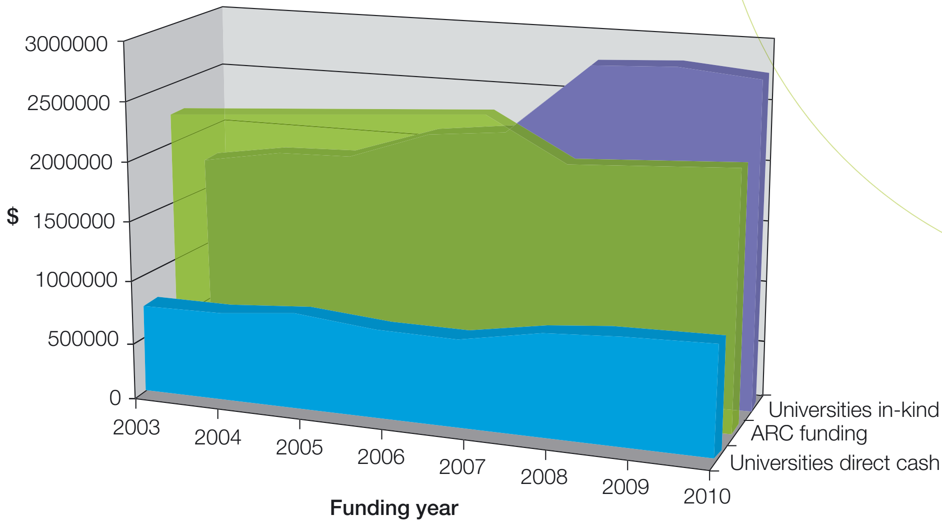
Andrew Ferris (2010 UQ PhD), Postdoc at University of Queensland and Universite de Sherbrooke, Quebec

Saeed Ghanbari (2008 SUT PhD), CSIRO Marine and Atmospheric Reserch, Melbourne

Russell Anderson (2010 SUT PhD), Postdoc at Monash University

Lesa Byron (2010 ANU PhD), Medical Physicist, Geelong Hospital

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



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 by multiple groups with independent research grants. The evidence lies in the international impact we have created as shown in the details covered in our KPM section [p.60].

ACQAO developed the topic of quantum-atom optics as the major strategic areas in our host universities. Throughout the life of our Centre the support by the host universities has increased, new staff positions have been created and we received several additional equipment grants. The universities value our work, see the importance of our research, 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.a 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 been modelled on our example.

We have established intensive research links and student networks with these two Centres in Europe and held seven successful student workshops between the three Centres with the next meeting in June 2011 in Germany. We have attracted the leading conferences in our field to Australia, the International Conference on Laser Spectroscopy (ICOLS) in 2003 and the International Conference on Atomic Physics (ICAP) in 2010 and made them extremely productive

The 'lecture room' of the Cape Tribulation International workshop events and showcases of Australian science. There is an ever-growing interest from young scientists across many countries to join our research teams. Over the eight years 40 international students and 16 international postdocs have chosen to work in the Centre, including three Alexander von Humboldt Fedor Lynen Fellows and a Fulbright scholar.

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 with three cotutelle (joint PhD projects), V.Delabert, J.Dugue and J-F.Morizur, supervised by M.Leduc, C.Fabre and N.Treps (LKB) with J.Close 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.

2. IFRAF in Paris and Laboratoire Charles Fabry, Palaiseau, on atomic four-wave mixing and metastable helium BECs, involving C.Westbrook and A.Aspect with K.Kheruntsyan, K.Baldwin and A.Truscott, and a joint DP project with J.Close and N.Robins

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

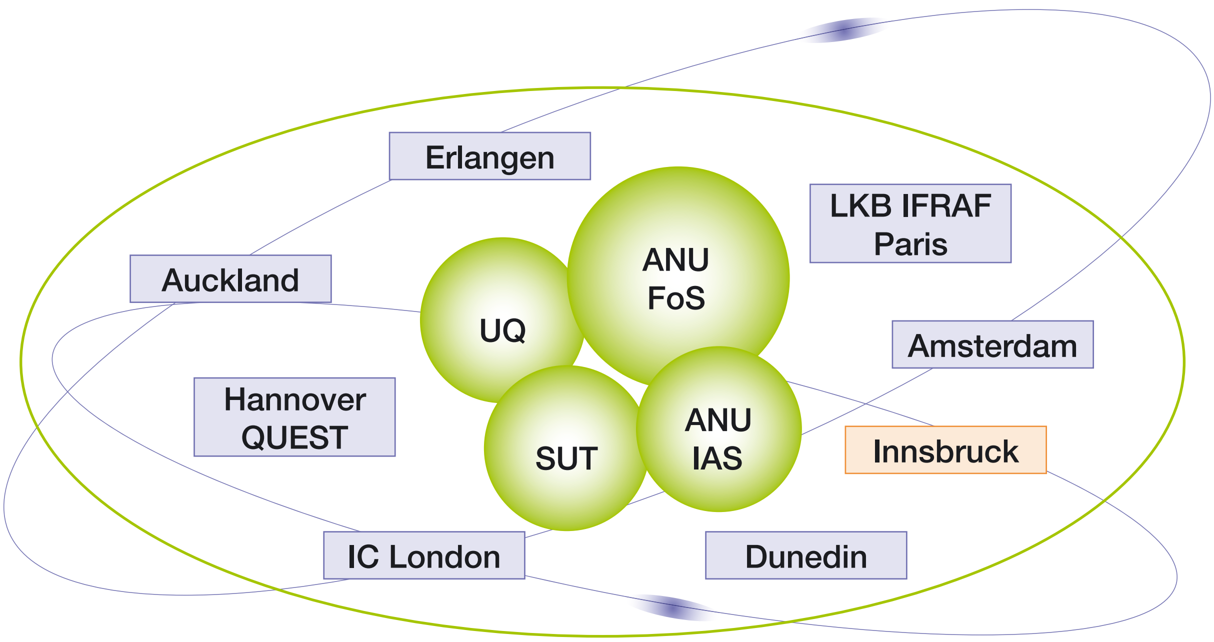
4. Amherst College, USA on two component BECs, R. Anderson (SUT) spent three months on collaborations with D.Hall.

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, and A.Sidorov on a six month sabbatical.

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



Official links and exchanges between the Centre and the international partners

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 and X.Liu)

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

ACQAO National workshop following AIP Congress, hosted at Monash University, December 2010.

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.

Looking to the future

Throughout the course of 2009 and 2010 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. This is an area where our Centre can build world-leading instruments and continue to be a driver for advancing the technology of clocks, frequency standards and of interferometric measurement of gravitational gradients beyond the limits imposed by quantum physics. At the same time we want to use the ideas and techniques developed in ACQAO for new emulations of real quantum systems and for more detailed fundamental tests.

Key Performance Measures (KPMs)

It can be expected that a Centre of Excellence demonstrates remarkable results and performance. The evidence for the excellent performance of our Centre is seen in 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.

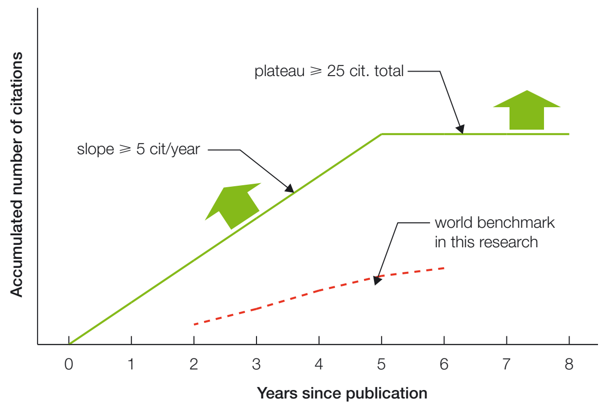
We are comparing our performance with the targets, initially set by the ARC in 2003 and then updated, and in several cases increased, in 2008. These targets set the expectation for world-class centres. We were able to not only meet all our targets but to exceed them in more than 65% of the 26 categories by a factor of two or more. These results are summarised in the table on page 63 which show the KPMs for 2010, both the results and the current targets, as well as the ratio between them. Performance that is higher than two times the target is highlighted in [dark green], and more than a factor of four is in [blue].

Our Centre has not only produced outstanding results in 2010 but is also consistent in its achievements, in many cases remaining well above target performance over its eight years of operation. To document this we present the long-term achievement ratio, (last column in the table on page 63), which is the average of the achievement ratios over all years of operation since 2003. This table shows that we consistently exceed our targets and initial expectations by more than a factor of two in at least 53% of all categories.

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. We achieved our goals in all projects and the results are reported in journals with the highest possible impact. Our publications include outstanding journals such as *Science, Nature, Nature Physics, Nature Communications and Review of Modern Physics*.

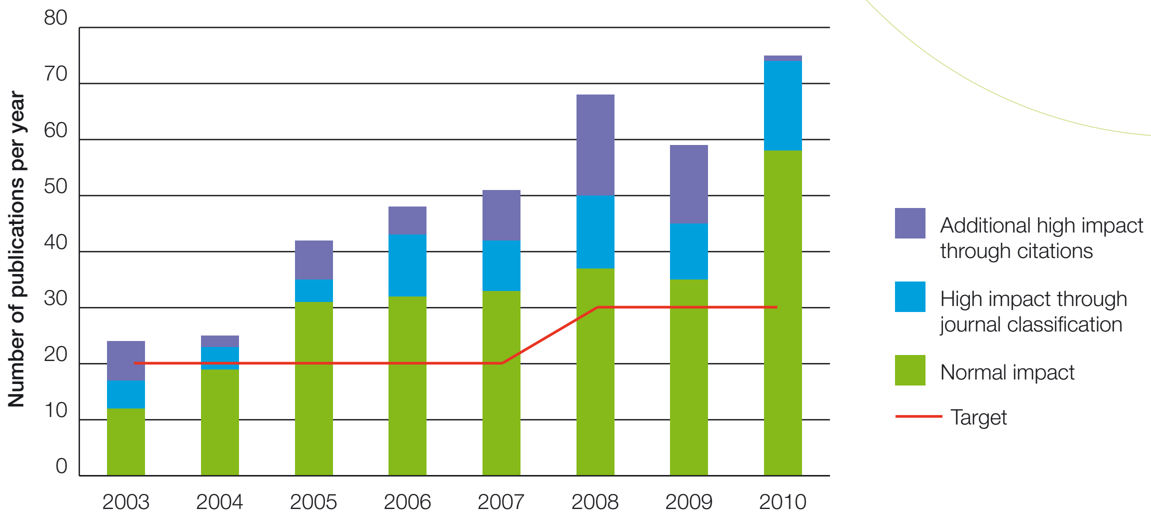
We focus on the quality of our results and compare them to global benchmarks in our field of research. ACQAO has a special KPM that evaluates the impact of our publications. We have defined high impact publications as: those published in high impact journals (impact factor>5) and those that actually have a high impact with more than 5 citations per year or at least 25 citations total during the lifetime of the Centre. Figure 1.b shows this definition and also shows the world benchmark of our field as used in the ARC ERA 2009 process. Our definition exceeds the benchmark by a factor of about 2.5.

Figure 1.b: ACQAO – definition of high impact



The steady increase in our productivity (see figure 1.c) is shown by the total number of publications in comparison with our KPM target (red line). While we reached a plateau in 2008 – 2010 in the number of our publications, this was consistent with a constant level of students and staff. The second feature is the number of high impact publications we produce. The rise from 2003 - 2008 is most impressive, with a strong finish in the final year. In particular, our younger publications have achieved a high impact and while it is still too early to measure the impact of our 2010 publications we can already see positive results.

Figure 1.c: ACQAO Publications



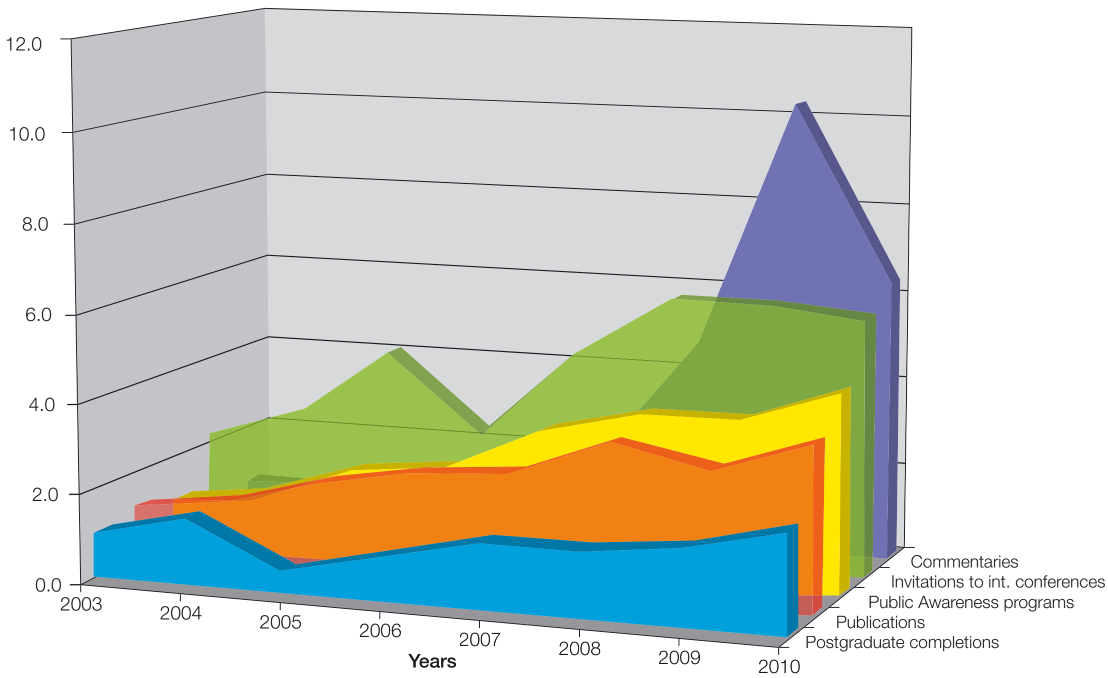
We are particularly proud of the international recognition our work receives, and the quality of our international links and networks. This is indicated by the impressive number of commentaries written about our results in 2010 (**19**), with a significant number of our 2010 publications (29) including international research collaborations, the large number of invitations (30) to ACQAO staff and students to present our research at conferences, visits to laboratories overseas (36) and the constant stream of international scientists and students who visit our Centre (18). Our staff actively contribute to many national and international committees (20) and we maintain a large number of active projects with international partners (18) each leading to joint publications, as shown on page 63.

Research training and professional education is one of our major strengths, with a good number of postgraduate students (9) completing their degree in 2010 while even more have been recruited in 2010. Many professional courses (7) and undergraduate courses (18) have been taught by our staff from the three host universities. In addition, we delivered a wide range of public awareness programs to the wider public (20), which are described in more detail on page 64.

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 primarily on fundamental research for the public domain.

It takes time to build a Centre such as ACQAO and we now demonstrate the positive effects of operating as a COE through the trends in our KPMs - Figure 1.d shows the results, normalised to the 2003 targets, for several important categories. While the input, in terms of funding and number of people, has remained fairly constant from 2007, the outcomes and the recognition of our work has increased remarkably. This is evidence of the high impact success of our Centre of Excellence.

Figure 1.d: Core KPM's normalised to 2003 targets.



Key Result Areas and Performance Measures

Key Result Area	Performance Measure	Target	2010 results	Achivement ratio 2010	Achievement ratio 2003 - 10
Research Findings and competitiveness	Quality of publications	6	10	1.7	2.5
	Number of publications	30	75	2.5	2.1
	Number of patents	0.3	1	3.3	2.1
	Invitations to address and participate in international conferences	5	29	5.8	4.9
	Invitations to visit leading international laboratories	8	36	4.5	4.5
	Number of commentaries about the Centre's achievements	3	19	6.3	3.3
	Additional competitive grant income (# applications submitted)	8	22	2.8	2.1
Research training and professional education	Number of postgraduates recruited/year	5	6	1.2	1.8
	Number of postgraduate completions/year	6	9	1.5	1.2
	Number of Honours students/year	5	2	0.4	1.2
	Number of professional courses	2	7	3.5	3.3
	Participation in professional courses	3	6	2.0	1.6
	Number and level of undergraduate and high school courses in the Priority area(s)	7	18	2.6	2.5
International, national and regional links and networks	Number of papers published with international co-authors/reports for internatioinal bodies	7	29	4.1	4.6
	Number of international visitors	15	18	1.2	1.9
	Number of national workshops/year	1	2	2.0	1.6
	Number of international workshops/year	1	4	4.0	1.9
	Number of visits to overseas laboratories	25	41	1.6	2.8
	Number of memberships of national and international professional committees	2	20	10.0	9.5
	Research projects with international partners	4	18	4.5	4.8
	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	1	0.5	0.6
	Number of government, industry and business briefings	2	4	2.0	1.8
	Number of Centre associates trained/ing in technology transfer and commercialisation	1	0	0.0	1.0
	Number of Public Awareness programs	4	18	4.5	2.7
Organisational Support	Number of new Organisations recruited to or involved in the Centre	1	2	2.0	1.3

<1 1<2 2<4 >4

Media, Outreach, and Awards

Our Centre is in a unique and privileged position to present our innovative science to the public. In 2010, ACQAO staff and students once again participated in a variety of outreach activities, received numerous awards and appeared in various media channels. The global developments happening within 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:

This year various media channels continued to be a source of outreach activity. The Centre's web presence continues to be a strong point with a number of online sites reporting our work, a sample is presented on page 66. Several radio appearances included Hans Bachor on the ABC Southeast broadcast, and during ICAP2010 the local ABC radio conducted a number of short interviews with Centre staff and selected international guests. At the ANU the He* BEC group received wide media coverage at the start of 2011 for their work on third-order coherence in BEC.

Outreach:

Across the world, the scientific community celebrated 50 years of lasers with numerous LASERFEST events happening. As part of the global effort of outreach, Professor Hans Bachor in collaboration with the Australian Institute of Physics, undertook a road show, presenting a series of talks about the laser, its history and what exciting things the future holds. A variety of locations included a water theme park in Western Australia and a special public event at Questacon in Canberra.

Hans Bachor with Excited Particles Questacon staff member Patrick Healan, presenting 50 years of lasers

The 22nd International Conference on Atomic Physics (ICAP), held in Cairns during July was the pinnacle of ACQAO's collaboration and outreach activities. Throughout the week of ICAP numerous radio and local news covered the event. Cairns mayor, Val Schier, opened the conference with the program including a number of Physics Nobel Laureates. As part of ACQAO's role, outreach activities included a special visit to the local high school where Nobel Laureate, Professor Wolfgang Ketterle from MIT talked about Physics to eager students.

Professor Ketterle from MIT encouraging students about the joys of science

During 2010, ACQAO staff and students participated in a variety of outreach activities. Academics from both ANU and UQ regularly visit local schools to present science. These activities contribute towards the goal of inspiring the interest of our future generation into the field of science. 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 (www.scientistsinschools.edu.au/contacts.htm.)

Professor Ping Koy Lam presented to a group of 100 lively students at Nanyang Junior College, Singapore. He shared with them aspects of his life since leaving the college in 1985.

Ping Koy talks Quantum Physics to Singapore students

In ACQAO's endeavour to support student run programs, we provided support to the KOALA workshop through sponsorship and travel funds to our students. Students from the Optical Society of America chapter at the University of Otago ran the program, highlighting the successful international collaboration that is happening within this 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 young college students from across Australia to explore their passion for science as a career for the future. All of these events provided a great opportunity to promote ACQAO's achievements.

Awards:

During 2010 a number of students gained recognition for their work, demonstrating the exceptional quality of future leaders that ACQAO has had the privilege to train.

Joint NLPC / National University of Singapore PhD student, Dario Poletti, who worked with the ACQAO IAS theory group has been awarded the inaugural Materials Research Society of Singapore Medal for 2009/2010. The award is for the most outstanding PhD thesis in the Department of Physics (NUS).

Seiji Armstrong from the Quantum Imaging group was a recipient of Prime Minister's Australia Asia Endeavour Awards.

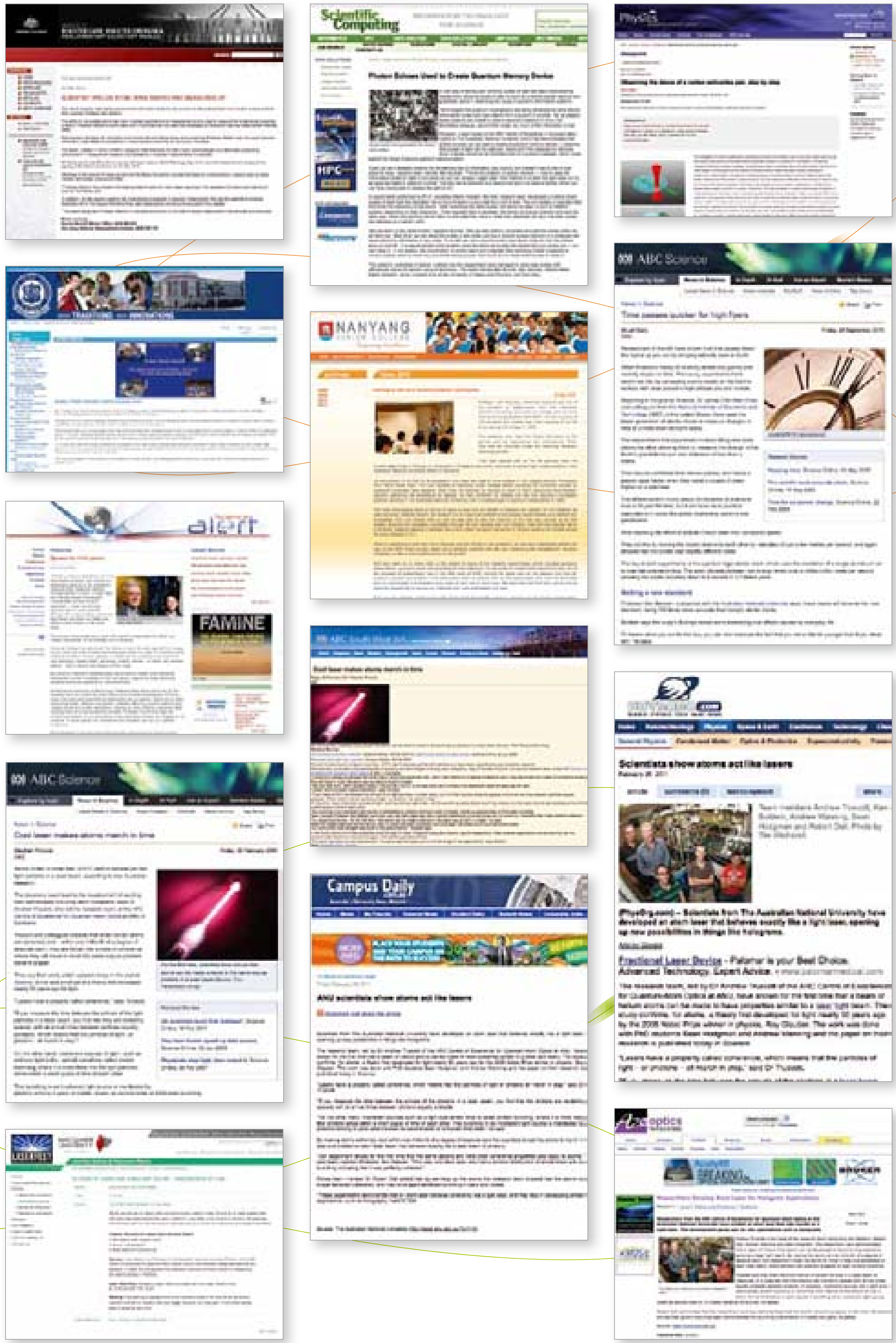
Mahdi Hosseini from the Atom Light Entanglement group won the RSPE Directors award for best PhD presentation as part of the John Carver seminar series.

In addition to our students' success, our staff from across the Centre continue to gain recognition for their contribution to Physics. Professor Hans Bachor from the ANU was awarded the AOS Beattie Steel medal and the AIP/IOP Harrie Massey award in recognition of his pioneering research on quantum-optics in Australia.

Associate Professor Matthew Davis received The University of Queensland Citation for Outstanding Contributions to Student Learning in recognition of his contribution to the quality of student learning and engagement, and the overall student experience at The University of Queensland. Professor Craig Savage was awarded the Australian Learning and Teaching Council Citation for Outstanding Contributions to Student Learning.

Hans Bachor is presented with Beattie Steel and Harrie Massey awards

In conjunction with the celebration of World Metrology Day, Professor Ken Baldwin was awarded the Barry Inglis Medal for 2010. This medal is an annual award that celebrates outstanding achievement in measurement research and/or excellence in practical measurement by an individual or group in the fields of academia, research or industry in Australia.


Scientific Computing
Photon Echoes Used to Create Quantum Memory Device
ABC Science
Time passes quicker for high flyers
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Mr	John	DEBS	PhD
Mr	Graham	DENNIS	PhD
Mr	Daniel	DÖHRING	PhD
Mr	Mahdi	HOSSEINI	PhD
Mr	Michael	HUSH	PhD
Mr	Gordon	McDONALD	PhD
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Mr	Mikhail	EGOROV	PhD
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Mr	Valentin	Ivannikov	PhD
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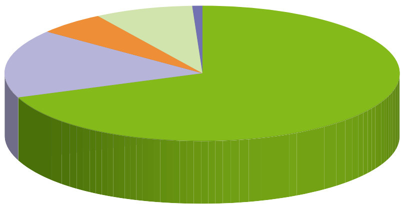
Mr	Prince	SURENDRAN	PhD

2010 ACQAO Annual Report Finances

Available funds as at 1 January 2010	$1,303,180

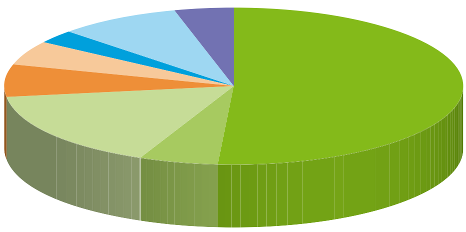
ACQAO Income in 2010	
Australian Research Council	$2,167,518
University contributions	
The Australian National University	*$509,000*
University of Queensland	*$170,000*
Swinburne University of Technology	*$253,334*
Subtotal - University contributions	**$932,334**
Other revenue	$22,716
Total Income	**$3,122,568**
Available funds	**$4,425,749**

ACQAO income 2010



ACQAO Expenditure in 2010	
Academic salaries	*$1,852,515*
PhD	*$195,911*
Admin. and Technical salaries	*$585,559*
National travel	*$240,243*
International travel	*$185,687*
Large equipment	*$101,216*
Research materials	*$306,095*
Operations and marketing	*$146,326*
Total Expenditure	**$3,613,552**

ACQAO expenditure 2010



Balance of funds 31 December 2010	**$812,197**

In-Kind contributions toward the Centre	
The Australian National University	$1,109,009
Swinburne University of Technology	$1,175,286
University of Queensland	$469,895
Total	**$2,754,189**

Projected financial activity in 2011

Available funds as at 1 January 2011	**$812,197**

ACQAO Income in 2011	**$0**

ACQAO Expenditure in 2011	
Academic salaries	*$262,416*
PhD	*$76,250*
Admin. and Technical salaries	*$62,400*
National travel	*$15,000*
International travel	*$18,000*
*Large equipment**	*$173,015*
Research materials	*$85,000*
Operations and marketing	*$20,000*
Total Expenditure in 2011	**$712,081**

Predicted balance of funds as at 31 March 2011	**$100,116****

* This includes purchases made in 2010 and paid in 2011.

** All ARC funds were spent by March 2011, the balance of funds being University contributions. These funds will be used to support transition activities from the current Centre of Excellence operation, in agreement with the ARC and participating Universities.

Previous ACQAO Annual Reports