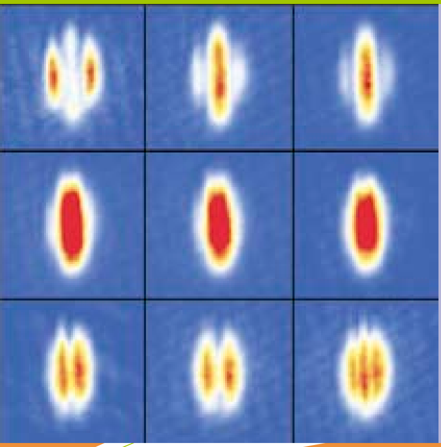

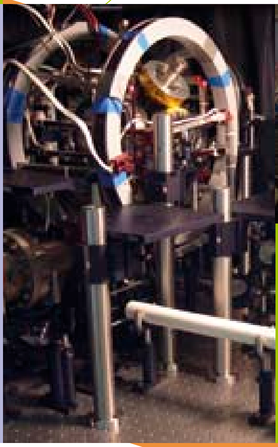

The Australian Research Council Centre of Excellence for Quantum-Atom Optics

Annual Report for the year 2008

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THE UNIVERSITY OF QUEENSLAND
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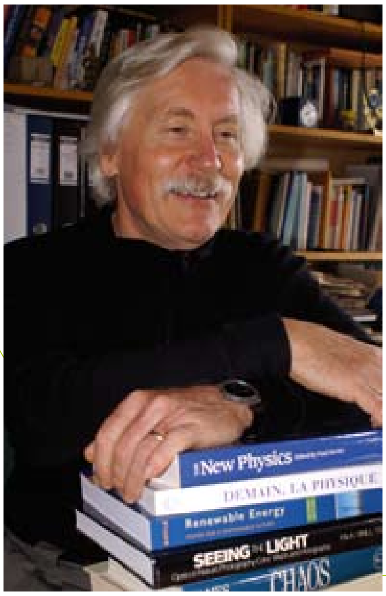


Quantum-Atom Optics is at a crucial point between fundamental research and the development of new practical technologies. It combines diverse concepts and expertise: the technology of optics and photonics, the physics of ultracold atoms and condensed matter systems, and the unique concepts of the quantum world. It is no surprise to see this research field expanding rapidly across the world. In a globally competitive field the Australian Research Council Centre of Excellence for Quantum-Atom Optics (ACQAO) is a key part of Australia's contribution to the development of the emerging field of quantum science and technologies. Our research is set to expand existing classical communication, information processing, imaging and sensing technologies.

ACQAO has been one of the first to combine these diverse directions in physics. It has been the launching pad for many of the research activities in this area. In Australia, we are known as one of the major contributors to this strategic research field. We are concentrating on fundamental science, both theory and experiments, and are creating the scientific tools for the engineers of the future, who will utilise the quantum properties of photons and atoms.

Our strength is that we understand and can demonstrate the special quantum properties of large objects, involving thousands or even millions of atoms or photons. We can observe the transition from the microscopic world of few particles to the macroscopic classical world. We are investigating, step by step, the way quantum rules extend to practical systems. Optics with visible light and ultracold atoms are the media of choice since the quantum effects dominate over conventional limitations, such as thermal noise.

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

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

ACQAO combines in a unique way expertise in the quantum properties of light and atoms, the theory of quantum statistics and nonlinear interactions with the operation of non-classical light sources, Bose-Einstein Condensates (BECs) and atom lasers, which are quantum systems of many atoms. Now in our seventh year of operation, we are gaining the benefits from long-term investments in people and laboratories. We started in 2003 with a series of ambitious projects focused on specific questions and technologies. In 2009, we have achieved these research goals, have published our results, made them available to our colleagues and are now fully involved in the second generation of projects. These follow closely, and in some cases even influence, the international agenda in quantum physics.

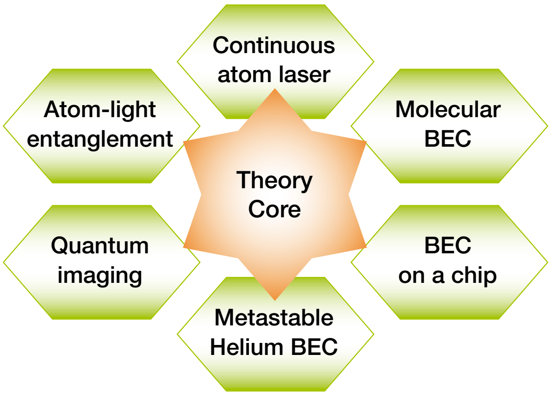
The details of our research are summarised in this report. Highlights for 2008 are numerous and include the demonstration of a pumped atom laser, universal laws for the statistical properties of Bosons and Fermions, the dynamics of ultra cold Bose gases, the theory of spontaneous vortices formation in BECs, the demonstration of spatial EPR in laser beams, the precision measurement of very long lived atomic states, Bragg spectroscopy of a strongly interacting Fermi gas, the demonstration of a new quantum process for information storage, the theory of collisional control of polar molecules.

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

Hans-A. Bachor

Professor Hans-A. Bachor
Research Director

Quantum-Atom Optics — background and research highlights



Our research goals

Optics and Photonics shape many aspects of our modern lives through the development of new technology. In recent years, many technologies have started to approach limits of performance given by the quantum uncertainty of light, introduced by the statistics of a stream of photons. Our fundamental research is developing methods that allow us to get around these quantum limits. At the same time, there are new applications, with the concept of quantum encryption being the most prominent, 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.

Quantum optics combines the particle and wave aspects of light and thereby offers new possibilities for the communication and processing of information. By using squeezed light we can get around the normal quantum noise limit and can improve the noise limitations of communication links and sensors [p. 20]. This can improve the signal to noise level of sensors and the channel capacity of communication lines, resulting in more efficient communication systems.

We have applied this concept not only for light but also for atoms. 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. Now, atoms can be manipulated, cooled and stopped and they can be detected individually, one at a time with increasing efficiency. However, atoms also have wavelike properties, they can be described by quantum mechanical wave functions and the interference between their probability amplitudes. The quantum wave nature of atoms is used both to create new atomic systems and for practical applications.

Australia has established a strong international research profile in this field, both through pioneering theory work as well as state of the art experiments. In ACQAO, we have built atom lasers that produce coherent matter waves. Soon, we will be able to study the quantum statistical properties of atoms in a way similar to optics. This opens the way for new examples of quantum technology, such as improved sensors based on atom interferometry that allow 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, and applies to other atomic species. We have contributed to the rapid progress in the experiments and the theory of quantum degenerate Fermionic atomic systems. It is now possible to build molecular Bose-Einstein condensates and to investigate the properties of dense Fermionic systems in the laboratory.

Entanglement

Entanglement is one of the key concepts of quantum physics. It describes the properties of two systems, which originate from one source, and are in the ideal case indistinguishable. For example, these could be two laser beams created in one source, propagating into different directions and which contain identical information, modulation and noise or they could be two, or more, beams of light, sets of particles, BECs, and atom laser beams that have identical properties.

Researchers in ACQAO have expanded the fundamental understanding of entanglement and its applications to practical systems. The ANU team has built optical sources that produce strong noise suppression, and entanglement. They use this special light to demonstrate spatial effects, such as the precision measurement of the position and direction of laser beams and the communication of spatial information. We have now succeeded in demonstrating such spatial entanglement [p. 10] and show that it satisfies the criteria discussed by Einstein, Podolsky and Rosen in the 1930s. We have extended this work to very elegantly produce and detect entanglement of spatial modes within one beam [p. 11].

Entanglement between individual atoms has been studied in detail and we are now asking the question how can we describe and generate entanglement between many particles. The ACQAO UQ team has extended two well-known criteria for continuous variable entanglement to situations where there is no classical local oscillator available to make the quadrature measurements, and developed a measurement scheme for demonstrating entanglement between two Bose-Einstein condensates that is experimentally realisable [p. 11].

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 such as Rubidium 87 and metastable Helium 4 will make a rapid transition into a new state of matter once they cool below a critical temperature. This is a so-called Bose-Einstein Condensate (BEC) that has properties vastly different from a thermal cloud of cold atoms. We have developed techniques to study the details of this transition both in experiments and through simulations.

The theory teams are modeling the dynamics and statistics of the BEC in great detail. The UQ team, in collaboration with the experimental group of Brian Anderson at the University of Arizona, provided conclusive experimental and theoretical evidence for the spontaneous appearance of vortices in the formation of a BEC [p. 39]. This team, with collaborators at the University of Otago, wrote and published an extensive review article in Advances in Physics on the development and application of ‘classical field’ methods for describing quantum and thermal dynamics and statistical mechanics of Bose gases [p. 26].

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

For example, the SUT group studies the dynamics of a two-component Rubidium (Rb) condensate localised in a microtrap on an atom chip. Two overlapping and phase-coherent BECs represent a rich quantum-mechanical system where the dynamical evolution of amplitudes and phases is governed by mutual nonlinear interactions. Using a Ramsey interferometer, they investigate the quantum state and reveal the dramatic appearance of a spatial dependence of the relative phase with time. The experimental observations show remarkable agreement with the numerical simulations of the coupled Gross-Pitaevskii equations and the predictions of mean-field theory [p. 35].

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 atom interferometry.

In 2008, the success of the Rb atom laser team at ANU in producing a pumped atom laser [p. 12] has received extensive media interest. This team continues to study the pumping mechanism in more detail, developing the atom laser further by producing a two state Raman output coupler. They used the atom laser as the source for a Ramsey type interferometer and as a probe for measuring the scattering length of Rb atoms [p. 16].

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 [p. 15].

ACQAO now has two ultracold metastable Helium facilities, one of which was used to perform fundamental tests on atomic structure as a test of the theory of Quantum Electrodynamics (QED). The transition rates to the ground state from key excited states in Helium have been measured — some for the first time — and provide excellent corroboration of QED predictions with <<10% uncertainty. This includes an accurate determination of the 2^3S_1 metastable with the longest lifetime of any neutral atomic state yet measured [p. 43].

From Bosons to fermions

Recent years have seen a very rapid development of the theory concepts and the experiments with fermions. In 2008, a major highlight was in the theory of strongly interacting, ultra-cold fermions. This included a major breakthrough in exactly solving the one-dimensional polarized Fermi gas problem, thus explaining some controversial experimental results from Rice University and pointing the way towards discovery of the long-awaited modulated or FFLO phase expected in these systems [p. 32].

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 fermion interactions using Bragg scattering. Using the properties of magnetic Feshbach resonances, they have investigated experimentally the transition from BEC to the regime of Cooper pairs [p. 31].

Bridging Quantum Optics and Atom Optics

ACQAO combines, in a unique way, quantum optics and atom optics, through theory and experiments. We have developed a clear vision and detailed plans for a novel apparatus that converts quantum correlations from optical laser beams to quantum correlations in atom laser beams. We are also investigating ways of transferring quantum correlations from light to atoms and vice versa as an initial step in designing atomic storage for optical quantum information. Our novel proposal of using the concept of photon echoes for storing and retrieving quantum information has been very successful in delaying and storing information [p. 23] and the ANU team has been able to test the quantum properties of storing quantum information via electro-magnetically induced transparency (EIT).

Leading the way to the future

All these experimental goals are underpinned and frequently initiated by a very strong theory core in ACQAO, which combines the expertise of world-renowned researchers. The different techniques and expertise from quantum optics, field theory and 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 the control and transport of matter waves in periodic driven potentials with broken time and space-reversal symmetries, optical ratchets [p. 38] and our research into the many-body physics of Josephson coupled BECs. Our theoretical predictions of resonant tunneling and interaction blockade recently received experimental confirmation in Emmanuel Bloch's laboratory in Mainz, Germany.

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

ACQAO has built its success around the idea of combining separate scientific concepts, linking the leading scientists in Australia and by 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 continues to play 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.

The Nodes — Structure of the Centre

The Centre successfully combines leading Australian scientists in quantum atom optics, underpinned by a theory core that operates across all nodes interacting closely with each of the six experimental projects located at the Australian National University (ANU) and Swinburne University of Technology (SUT). Our team is based in three locations, Canberra, Melbourne and Brisbane, with links through joint scientific projects enabling the sharing of expertise and equipment and the exchange of people. Our team has demonstrated the importance of scientific collaboration. We maintain ambitious scientific goals and after achieving our initial goals in the first five years, our renewed goals are benefiting from long term investment.

Damien Hughes

The Centre is coordinated from the ANU by the Director, Hans-A. Bachor and the Chief Operations Officer (COO), Damien Hughes. Ms Ruth Wilson formally held this role to April 2008 when she retired. The science is carried out in the four nodes at ANU, SUT and the University of Queensland (UQ) with a total staff of 46 plus 49 students.

ANU FAC, Canberra

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

Some of the ANU FAC Node group — front row L to R: G. Dennis, R. Stevenson, M. Johnsson, J. Hope, C. Figl, R. Poldy, J. Close, P. Altin, M.Jeppesen; back row L to R: N. Robins, A. Carvalho, J. Debs, D. Doering

ANU IAS, Canberra

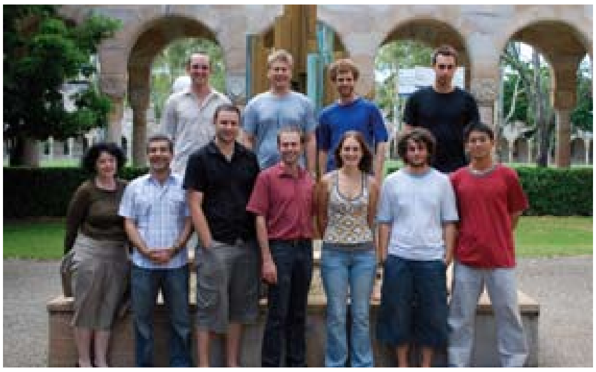
On the other side of the ANU campus, within the Research School of Physical Sciences and Engineering, the node combines theory and experiments. The laboratory now has a precisely controlled He* atom laser, making possible investigations of quantum interference in the atom laser output and feedback control of fluctuations in the atom laser intensity. The ultracold He* source has also enabled new measurements in precision spectroscopy, and will soon be able to study quantum statistical effects made accessible through the development of single atom detection techniques (Andrew Truscott, Robert Dall and Ken Baldwin, who is Node Director and Centre Deputy Director).

The IAS Node at ANU — clockwise from bottom: S. Hodgman, C. Lee, M. Matuszewski, L. Byron, K. Hicks, T. Alexander, E. Ostrovskaya, Y. Kivshar, K. Baldwin, D. Poletti, D. Bordeau

The theoretical group has world leading experience in non-linear optics, optical lattices and soliton physics (Yuri Kivshar, Elena Ostrovskaya, Tristram Alexander, Chaohong Lee), with their focus on the properties of non-linear interactions between matter waves and their effects in optical lattices and other periodic structures.

UQ, Brisbane

The Node at the University of Queensland (UQ) is located in the School of Physical Sciences, and is led by pioneering theorists (Peter Drummond, Joel Corney — Node Director, Matthew Davis, Karen Kheruntsyan, Murray Olsen, Margaret Reid, Xia-Ji Liu and Hui Hu). Their work includes quantum phase-space and classical field methods for the simulation of BECs, cold molecule formation, quantum correlation in low dimensional Bose and Fermi gases, fundamental tests of quantum mechanics, and the development of specialised software. There is a strong collaborative link with the ANU theory groups and connections to many aspects of the experimental projects in all the other nodes.



UQ Node — front row L to R: S. Golding, K. Kheruntsyan, M. Davis, J. Corney, S. Midgley, J. Sabbatini, C. Feng; back row L to R: M. Garrett, G. Lee, C. Foster, S. Haine (Absent: A. Ferris, A. Sykes, M. Ögren, M. Olsen, X.-J. Liu, H. Hui, T. Haigh, S. Hoffmann, D. Barry)

SUT, Melbourne

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

SUT Node — front row L to R: A. Sidorov, P. Drummond, Q. He, S. Jose, P. Hannaford, M. Reid, W. Rowlands, M. Kivinen, M. Mark; back row L to R: R. McLean, T. Tchernova, A. Akulshin, B. Dalton, M. Egorov, B. Hall, P. Dyke, C. Vale

Linkages across the Centre

Each node is linked through several joint scientific projects that include the following;

- BEC on a chip (ANU IAS, SUT);
- Single atom detection, funded by LIEF (ANU FAC, SUT, UQ);
- Quantum correlations with fermions (ANU FAC, UQ);
- Fermion statistics (UQ, SUT).

We have also established close linkages with external parties, including ADFA (Dr C. Harb), UQ (Prof. H. Rubinsztein-Dunlop and Dr W. Bowen) and DSTO (Dr D. Pullford), highlighting our interest in building strong research based on key collaborations.

In addition to the personnel mentioned here, the Centre includes a number of postdoctoral fellows, graduate students and visiting fellows — all listed on pages 60–62. The collaborative team spirit that exists between these people has contributed to the success of ACQAO. As well as its strengths in fundamental science, the Centre enjoys the benefits of a strong administrative team. The administrators include Stephanie Golding (UQ), Tatiana Tchernova (SUT) and Kathy Hicks (ANU IAS), each working closely with our COO in coordinating and managing the administrative duties of the Centre.

Governance

Thanks to the continued funding from the Australian Research Council (ARC), we started 2008 with renewed ideas and goals. With an extended opportunity to make significant contributions to the field of Quantum-Atom Optics, ACQAO was able to gain further ongoing support from our host universities. Significant support from ANU, SUT and UQ has been combined with ARC funds to leverage our existing achievements to new levels (see Finance summary pages 58–59). We continue to operate with our well tested governance structure.

The Research Director, Hans-A. Bachor, is responsible for the overall science direction and performance of the Centre. The Chief Operations Officer (COO) is responsible for all operational and financial aspects of the Centre. Ms Ruth Wilson, who had greatly contributed to the Centre since inception as the COO, made the decision to move into retirement. Mr Damien Hughes has since replaced Ruth in this position, ensuring the legacy left by Ruth is continued and would grow with our renewed funding position.

The fundamental decisions for the Centre are determined by all Chief Investigators (CI) via our bi-annual CI meetings (ANU, May 2008 and Lorne, November 2008). The Executive Committee supervises the ongoing administration and meets four times a year. The Executive Committee includes the Research Director, COO, Node Directors (Ken Baldwin, Peter Hannaford and Joel Corney) and the Scientific Directors (Peter Drummond and Yuri Kivshar).

Node Directors are responsible for the continuous operation of the four nodes. The CIs hold regular fortnightly informal science meetings within the nodes across all of the projects.

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

Centre Management Meetings

Meeting style	People	Frequency	Location and Month
CI meeting	All CIs & COO	Bi-annual	Canberra, May Lorne, November
Executive Committee	Research Director, COO, Node Directors & Science Directors	Quarterly	Canberra (January, April, July, September)
Advisory Board	International & National members	Annually	Canberra, May (National members)
International Workshop	Centre staff & students, Centre Partners & other Australian research groups	Bi-annual	Beijing, September Lorne, November
Individual Projects & groups	CI, Research Fellows, students & visitors	Fortnightly	
IP Committee	Node Directors, Participating Universities	Annually	Canberra, May

Advisory Board

ACQAO is privileged to have key international and national expertise as members of its advisory board. The members of the advisory board support the Centre through scientific input and advice on potential end-user applications for our research. Our international members have helped build awareness of our activities in Europe and the USA including participation in our workshops. The national members combine both government and private enterprise and enhance our linkages with key stakeholders interested in our research.

We remained in close contact during 2008 with our international members including a visit by the Chairman of the international advisory board, Prof. A. Aspect, in December 2008.

International Advisory Board members

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

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

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

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

Professors Bill Phillips, Alain Aspect, Eugene Polzik

Prof. Keith Burnett

National Advisory Board members

We are thankful to Senator Gary Humphries and Bob McMullan MP for their support over the years as they concluded their participation on the board at the end of 2007.

We also welcome our new board members: Lawrence Cram, Mark Dransfield, Peter Fisk and Warren Marwood. Their feedback during the May 2008 National Board meeting was crucial to our future planning and goals, in particular by analysing and commenting on our plans for the long term development of practical instruments based on quantum and atom optics.

Participants in the May National Advisory board meeting

Prof. Lawrence Cram, Deputy Vice-Chancellor, Australian National University.

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

Dr Steven Duvall, Technology Consultant.

Dr Peter Fisk, Acting Chief Executive and Chief Metrologist, National Measurement Institute (NMI), Department of Innovation, Industry, Science and Research.

Dr Warren Marwood, Deputy Chief Defence Scientist (Information and Weapons Systems), Defence Science Technology Organisation (DSTO).

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

Entangling the spatial properties of laser beams

K. Wagner[1], J. Janousek[1], V. Delaubert[1,2], H. Zou[1], C. C. Harb[3], N. Treps[2],
J. F. Morizur[1,2], P. K. Lam[1], and H-A. Bachor[1]
[1] *Department of Physics, ACQAO, CoS, The ANU*
[2] *Laboratoire Kastler Brossel, Paris Cedex 5, FRANCE*
[3] *Australian Defence Force Academy, Canberra, AUSTRALIA*

We have experimentally demonstrated entanglement of the spatial properties (position and momentum) of two laser beams [1]. We have achieved spatially entangled beams by combining a TEM$_{00}$ reference beam with a squeezed TEM$_{10}$ beam, and then entangling this beam with another TEM$_{10}$ squeezed beam. For each entangled beam, a measurement can be made on the TEM$_{10}$ component in order to find the beam position (real part) or the transverse beam momentum (imaginary part).

A direct measurement of the correlations between the two beams allows a calculation of the degree of inseparability. The two beams are entangled if these correlations are stronger than can be attained by classical means. The EPR (Einstein, Podolsky and Rosen) entanglement is measured by making predictions on what will be measured on one beam, based on a measurement of the other beam, and this is quantified by the degree of EPR paradox. An inseparability measurement of 0.51 and a degree of EPR paradox of 0.62 have been achieved, showing a genuine proof of the entanglement of position and momentum of two laser beams. The technology developed here can be used to make high precision optical measurements, or as a resource for new quantum information applications, particularly those that require multi-mode entanglement.

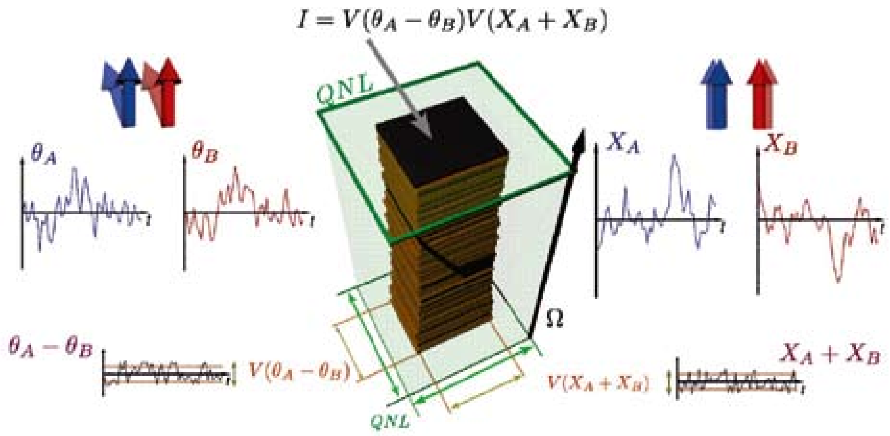


Fig. 1: No laser beam can have a fixed position or momentum. Spatial entanglement manifests itself as a strong quantum correlation between the position and direction of two beams, A (blue) and B (red). On the left, this illustration shows the fluctuating directions θ_A and θ_B of two beams, which are correlated, and on the right, the positions X_A and X_B, which are anti-correlated. For perfectly entangled beams the differences (θ_A-θ_B) and (X_A+X_B) would both be zero. Real entangled beams have a small residual differential movement. The variances $V(X_A + X_B)$ and $V(\theta_A - \theta_B)$ are calibrated against their respective quantum noise limit (QNL), which corresponds to the differential movement of two laser beams with independent quantum noise. A good measure of entanglement is the Inseparability, which for a symmetric system is the product $I = V(X_A + X_B)V(\theta_A - \theta_B)$. This is shown as the area of the filled rectangles in the centre of this figure. Each slice of the tower represents one measurement and the comparison of the area with the QNL (the green box) shows directly the degree of inseparability.

References

[1] K. Wagner et al., Science **321**, no. 5888, pp. 541 - 543 (2008).

Extending optical entanglement into higher dimensions

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

Optical entanglement is a key requirement for many quantum communication protocols. Conventionally, entanglement is formed between two distinct beams, with the quantum correlation measurements being performed at separate locations. Such setups can be complicated, requiring the repeated combination of complex resources, a task that becomes increasingly difficult as the number of entangled information channels, or modes, increases. We show entanglement between the spatial modes within one beam [1], see Fig. 1. Our technique is particularly elegant and a major advance towards practical systems with minimum complexity. We demonstrate three major experimental achievements: (i) only one source is required to produce squeezed light in two orthogonal spatial modes, (ii) the entanglement is formed through lenses and beam rotation, without the need of a beam splitter and (iii) the quantum correlations, see Fig. 2, are measured directly and simultaneously using one multi-pixel, quadrant detector.

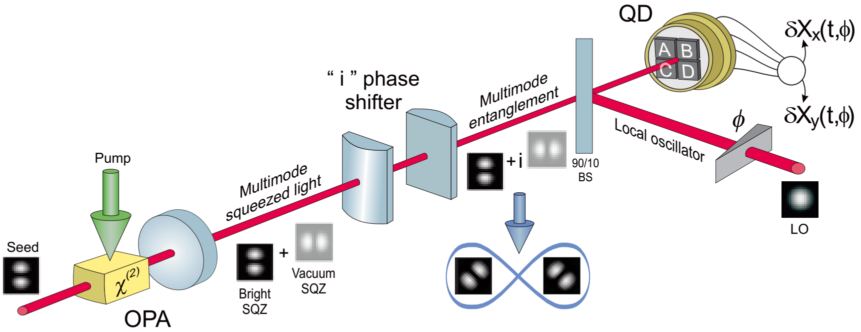


Fig. 1: Multimode entanglement experimental setup. We use a degenerate OPA for generating two squeezed higher-order modes. An optical system made of cylindrical lenses imparts a $\pi/2$ phase shift on one of the modes. Entanglement between 45° rotated spatial modes is analyzed using a QD set to a correct basis. $\delta X_x\,(t,\phi)$ is equivalent to $\delta X_{(A+B)-(C+D)}\,(t,\phi)$, and $\delta X_y\,(t,\phi)$ is given by $\delta X_{(A+C)-(B+D)}\,(t,\phi)$. OPA: optical parametric amplifier; LO: local oscillator; HD: homodyne detection; QD: quadrant detector.

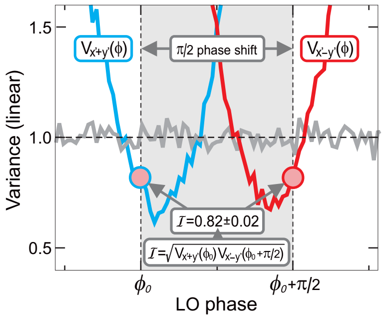


Fig. 2: Results for inseparability. Measurement of the variance for the sum $V_{x'+y'}\,(\phi)$ and difference $V_{x'-y'}\,(\phi)$ for the 45° rotated fields. The data, both below the QNL, are combined to one value for the inseparability of $\mathcal{I} = 0.82 \pm 0.02$, demonstrating significant entanglement between two orthogonal spatial modes within one optical beam.

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Pulsed pumping of a Bose-Einstein condensate

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Atom lasers are coherent matter waves that are derived from Bose-Einstein condensates and bear striking similarities to optical lasers. The main reasons for the importance of optical lasers are their unique coherence properties and high brightness that offer significant advantages over thermal light sources. In a very similar way, the atom laser is a promising device where a high brightness coherent atomic source is required. In the context of high signal-to-noise measurement processes, the achievable brightness of an atom laser may open the route towards unachieved detection senitivities.

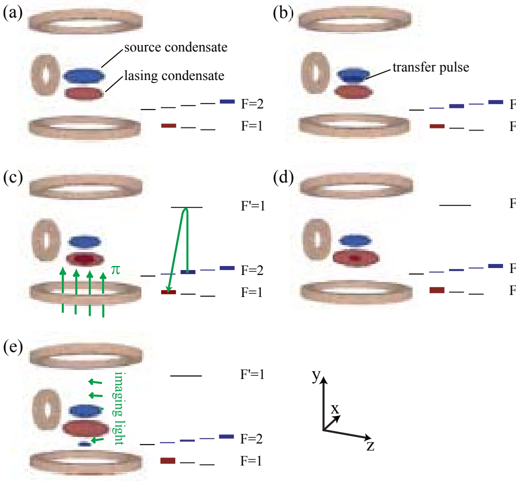

Fig. 1: Scheme for the pulsed pumping of a Bose-Einstein condensate.

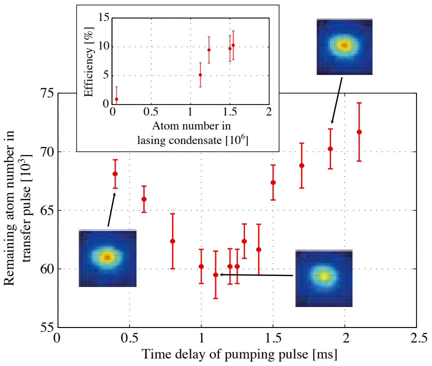

Fig. 2: Resonance depletion curve of the population in the transfer pulse.

In order to realize a truly high brightness and flux in atom lasers, it is crucial to implement a mechanism allowing for continuous operation of the device. So far, the average flux of an atom laser has been limited by the repetition cycle of the apparatus producing the Bose-Einstein condensate. An atom laser can only be output-coupled until the Bose-Einstein condensate that serves as a source (the lasing condensate) is depleted. For continuous operation, it is necessary to implement a mechanism that coherently replenishes the lasing condensate. Recently, our group has achieved such a pumping mechanism in the regime where the replenishment is realized at time scales corresponding to quasi-continuous operation of the atom laser (of the order of 100 ms) [1]. Our aim in this work is to isolate and measure the process that drives the pumped atom laser. We present results on this pumping mechanism operating in the pulsed regime [2]. A coherent population transfer between a source and a lasing condensate is realized by means of an atom laser transfer pulse (Fig. 1). The timescales of the population transfer are of the order of the frequency width of the condensates. This offers the opportunity to characterize the pumping mechanism in a different temporal regime and to use a different detection channel on the underlying process. As opposed to the work in [1], we detect the population transfer by measuring the depletion of the transfer pulse (Fig. 2) instead of an increase of atom number in the lasing mode after the pumping. Additionally, we measure the temperature of the lasing condensate after the pumping pulse. The data shows a clear resonance both in number and in temperature, proving a coherent transfer of atoms into the lasing condensate and shedding light onto the underlying mechanism.

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A two-state Raman coupler for coherent atom optics

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Making the analogy with light, a coherent, bright beam of atoms outcoupled from a Bose-Einstein condensate (BEC), known as an atom laser [1], is a promising tool for high precision atom interferometry [2]. Key to achieving maximum precision with an atom laser is the ability to maximise flux and minimise beam divergence. Previous work in our group has shown that by using a Raman transition to drive the outcoupling process, the flux limit is increased, and the divergence minimised [3, 4]. Furthermore, our theoretical calculations have shown that maximum flux is achieved by using a two-state outcoupling scheme [5]. However to date, Raman outcoupling has operated via three- and five-state schemes, by targeting transitions between Zeeman sub-levels in a given hyperfine manifold [6, 3]. We have developed a Raman laser-system that resonantly couples only two levels in different hyperfine ground states of ^{87}Rb [7]. Operated as an outcoupler, this system produces an atom laser beam in a single internal state with all the aforementioned advantages of Raman outcoupling.

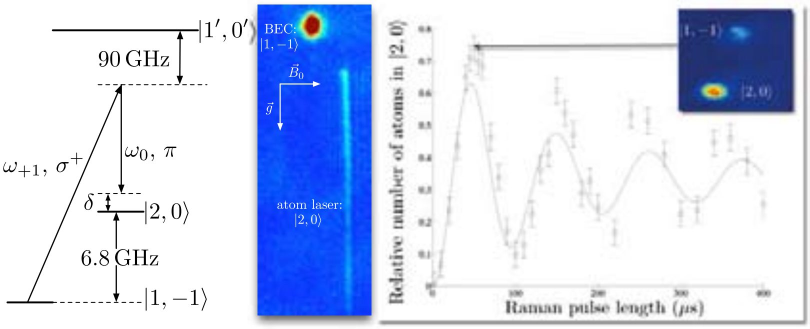

Fig. 1: The two-state Raman outcoupler. Left: The outcoupling level scheme. Middle: A typical absorption image for 5 ms of outcoupling. One of the Raman beams is directed horizontally, and the other vertically, thus transfering momentum to the atoms at 45° to gravity resulting in the parabolic beam trajectory seen. Right: Rabi oscillation of out two-state system. The oscillations decay due to the decreasing wavefunction overlap between the trapped and untrapped F=1 and F=2 states.

This versatile system has also been used as an internal state beamsplitter for atom lasers, and we have employed its use in our free space coherent Ramsey interferometer project also discussed in this report. Following the work of Haine et al. [8, 9], a rather interesting avenue of exploration is to use the Raman outcoupler to generate non-classical atom laser states, in direct analogy with squeezed light. This could be used to further boost the sensitivity of an atom interferometer, and to investigate massive particle entanglement when combined with single atom detection schemes.

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Actively stabilising the output of an atom laser

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Atom lasers have the potential to revolutionise future atom optic devices where a high brightness source of atoms is required. Indeed, continuous atom lasers may prove superior in precision measurements where presently optical and mechanical techniques are conventionally used. For this to become a reality, however, frequency and amplitude noise on the atom laser beam which limit its stability will need to be eliminated. As is the case for the optical laser, active stabilisation offers a possible solution to reduce noise on the output of an atom laser.

Here, we report the first implementation of active feedback to stabilise a continuous wave (CW) RF atom laser[1]. An error signal derived from ions produced during the formation of the atom laser, with appropriate gains and sign, is fed back to the RF output-coupler, locking the output-coupling surface inside the condensate. The noise we are correcting for is fluctuations in the magnetic trap bias which result directly in frequency fluctuations that manifest themselves as amplitude fluctuations on the atom laser mode. By actively compensating for this noise, the scheme reduces both frequency and amplitude noise on the atom laser and, in principle, also stabilises the spatial mode.

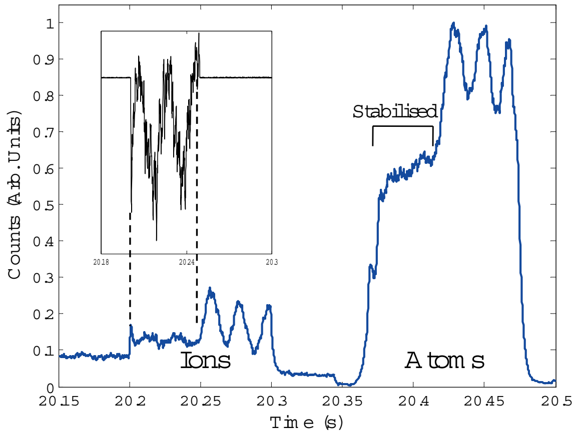

Fig. 1: Electron multiplier (EM) trace, averaged over four runs of the experiment, demonstrating stabilisation of the atom laser beam. The ion signal is first to arrive on the left of the trace, while the atom signal arrives $\sim$ 150 ms later which is the time of flight from the BEC to the EM. Shown in the inset is the output of our control circuitry.

In summary, we have demonstrated the first successful atom laser stabilisation scheme. Besides being able to stabilise the output of an atom laser, a similar technique might be used to stabilise oscillations in a BEC. In many BEC experiments, the trap frequency is altered and under some circumstances this can lead to excitation of unwanted modes. Since these oscillations can lead to density changes, they should be detectable in an ion signal, which could then be used to feedback to the relevant magnetic trap currents.

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Transverse Mode profile of Guided Matter Waves

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Recently, the guiding of atom laser beams output-coupled from BECs has been achieved using optical waveguides to confine ^{87}Rb atoms released from magnetic [1] and optical trapping fields [2]. In both cases, the output-coupled atoms were confined by far-red-detuned, focused laser beams aligned horizontally with respect to the condensate. The significance of these experiments is that the output-coupling mechanism allows the population of just a few transverse modes, with 50% [1] and 14% [2] in the transverse ground state.

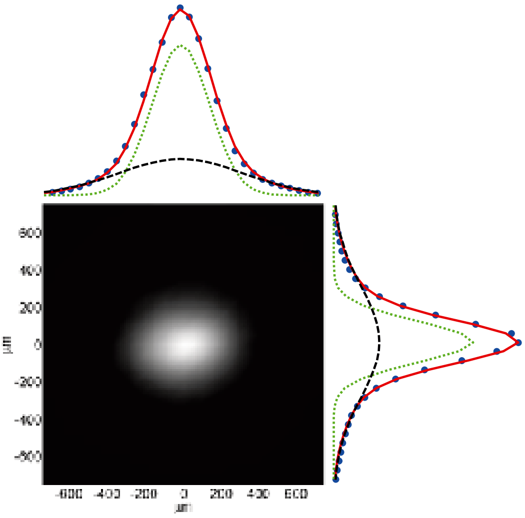

Fig. 1: Experimental image of the transverse mode of a guided atom laser. Both axes fit well to a double Gaussian, the narrowest being the lowest order mode of the guide.

In the experiments reported here, we are able to directly image - for the first time - the transverse mode structure of the guided matter waves by taking advantage of the high detection efficiency which is characteristic of metastable helium (He*) atoms. We are able to observe end-on to the guiding structure the transverse spatial profile of the atoms as they strike our detector, thereby allowing direct measurement of the guided matter wave mode structure.

The mode profile of a freely propagating atom laser beam is far from an ideal Gaussian. This is due to mean field interactions that generate ’caustics’ and interference fringes. In comparison, the mode profile from our single moded, guided atom laser, shown in Fig. 1, is spatially smaller resulting in an increase in flux of more than two orders of magnitude compared to the unguided beam. Moreover, the guided atom laser spatial profile approaches a Gaussian.

In Fig. 1, a least squares fit to the guided atom laser mode profile is shown. The fitting function comprises two Gaussians, the narrower of which represents the lowest order mode and the wider one representing the sum of the many higher order modes. This is analogous to fitting the condensate and thermal background for a trapped gas. In addition, since at finite temperatures a thermal component is always present in the source condensate, it is therefore expected that some thermal modes will also be populated in the guided atom laser.

In summary, we have taken the first images of the transverse profile of a guided atom laser, demonstrating an atom waveguide in which atoms are guided predominately (65 %) in the fundamental mode. We have shown that guiding the atom laser beam maintains the near perfect Gaussian mode profile by avoiding the formation caustics and interference fringes that are normally present in atom laser beams.

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A free-space Ramsey interferometer with Bose-condensed atoms

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Atom interferometry has proven to be an increasingly valuable technique for precision measurements over the last years. Compared to photons, atoms offer the advantage of having an intrinsically more complex structure and therefore allowing a larger range of possible measurements to be undertaken. There have been a number of fundamentally important experiments making use of the atomic mass to measure the Newtonian gravitational constant G [1] and the fine structure constant α [2].

Here, we show results on a free-space atom interferometer with Bose-condensed ^{87}Rb atoms, operating on the atomic clock transition $|F = 1, m_F = 0\rangle \rightarrow |F = 2, m_F = 0\rangle$ (Fig. 1) [3]. The interfering atoms are part of an atom laser that is output-coupled from a Bose-Einstein condensate and travels under gravity through a sequence of two Ramsey-type (internal state) beam splitters. The experiment offers the opportunity to make a comparison between traditional atomic beam interferometers and comparable devices using Bose-condensed atoms. Combining the existing pumped atom laser with a continuous replenishment system of the source condensate is a promising way to significantly increase the average atom flux. Furthermore, different schemes have been proposed for squeezing an atom laser, opening the route towards interferometric sensitivities below the standard quantum limit.

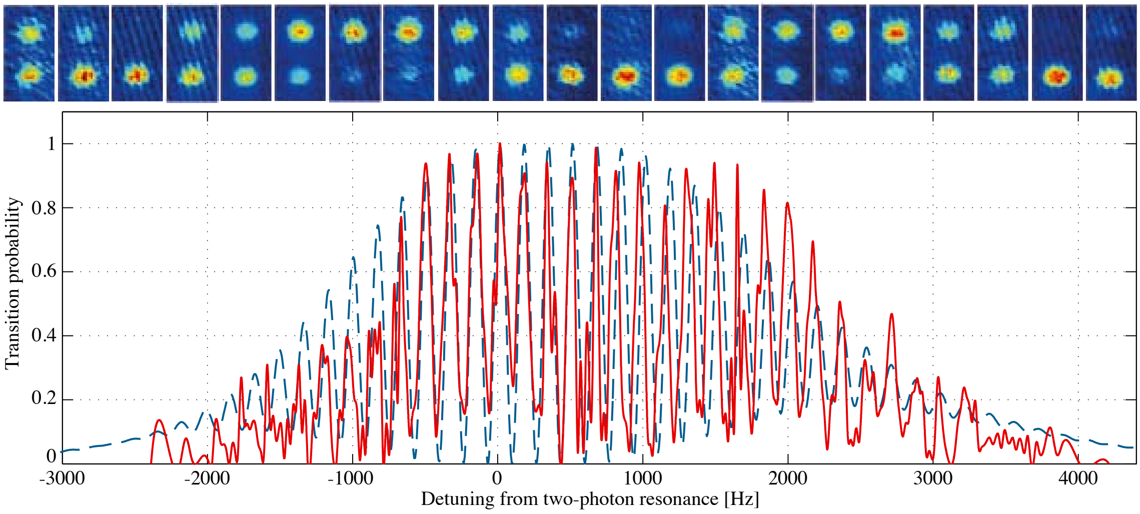

Fig. 1: Ramsey fringes measured over a range of 6.5 kHz. The red solid curve shows the experimental data set, whereas the blue dashed curve depicts calculations of the Ramsey fringes for comparable experimental conditions. The upper (lower) clouds of atoms in the absorption pictures above the graph show the population in the $|F = 2, m_F = 0\rangle$ ($|F = 1, m_F = 0\rangle$) state, for different detunings from two-photon resonance.

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Paired atom laser beams created via four-wave mixing

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Sources of matter waves gained a dramatic improvement with the achievement of Bose-Einstein condensation (BEC) in dilute gases and the development of the atom laser [1]. Like optical lasers before them, atom lasers can produce Heisenberg-limited beam profiles and promise high spectral density through their dramatically lower linewidth. Another exciting possibility resulting from having such a coherent source of atoms is the generation of non-classical matter waves through entangled beams. Such entangled beams are useful for tests of quantum mechanics, and are required to perform Heisenberg-limited interferometry. Here, we show that the asymmetric scattering rates between internal states of metastable helium (He*) cause well-defined peaks in the output of an atom laser. These peaks are due to a four-wave mixing (FWM) process, and are experimentally demonstrated.

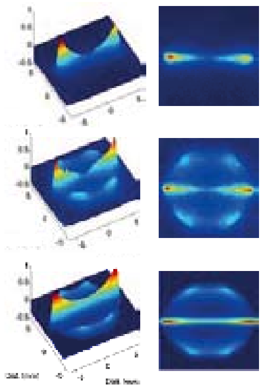

Fig. 1: First two rows show experimental atom laser spatial profiles observed on our MCP 4cm below the trap, in a 3-D rendering (left) and the 2-D image (right). Both sets of data were taken for an outcoupling detuning of 2 kHz, however the Rabi frequency is increased by an order of magnitude between the two sets. The upper row shows the usual He* atom laser, while the middle row demonstrates the appearance of the resonant scattering peaks.

Using existing sources of entangled pairs of atoms for interferometric experiments will be complicated by the high densities of the sources, where the nonlinearities that generated the correlations ultimately degrade the long term coherence of the sample. In our scheme, the nonlinear interactions are used to drive FWM in the magnetically trapped condensate, but the resulting untrapped beams that propagate in free space are dilute, potentially avoiding the decoherence problem. Using atoms in the untrapped state also makes the beams insensitive to magnetic field inhomogeneities. We show that pairs of beams can be produced simply by the process of radio frequency (RF) outcoupling from a He* BEC, without the need for Feshbach resonances, optical traps or scattering pulses. Unlike the previous methods, which required pairs of atoms travelling at high kinetic energies as a source, this process involves scattering between atoms initally in the same zero momentum state to create states with non-zero momentum. The energy-momentum resonance comes from the mean field conditions that are obtained during outcoupling from the condensate. Semiclassical and field theoretic simulations of the experiment show that the beams are generated by the same FWM process that generated entangled atom pairs in the earlier experiments.

In summary, our experiments show that appropriate outcoupling from a He* BEC can produce well-defined additional peaks in the output beam. Field theoretic and semiclassical models show that these peaks are formed from scattering of pairs of atoms in BEC, and are therefore entangled upon formation. The potential advantages of these correlated beams are that they are spatially well separated from the background of the atom laser and that the quasi-continuous dilute beam will likely remain coherent over larger timescales than trapped fields.

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Quantum noise and entanglement in Bose-Einstein condensates

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

1. We have analysed an experiment that observed the formation of multiple 3D bright solitary waves (BSWs) in the collapse of a BEC when the interaction strength was switched from being positive to negative [2]. Mean-field theory predicts that the solitary waves should form with the same phase, but the experimental results suggest that in fact they have repulsive phase relations. We have found that quantum noise can result in effective repulsive interactions between solitons in one dimension, but not in three dimensions [3].

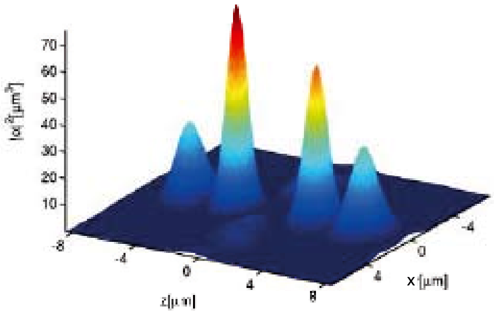

Fig. 1: Bright solitary waves formed in BEC collapse.

2. We have investigated the creation of entangled matter-wave packets in the degenerate four-wave mixing of a BEC in a moving 1D optical lattice. In this process, atoms from a mother condensate form two entangled daughter condensates with differing momenta. Phase-sensitive homodyne measurements of the atomic fields are necessary in order to prove entanglement between the atomic pulses. This requirement has lead us to develop three new entanglement criteria for use with non-classical local oscillators [4]. We have made use of this scheme in simulating a 1D version of degenerate four wave mixing and developed and analysed an experimental measurement scheme to demonstrate both inseparability and the EPR paradox [5].

3. We have simulated and analysed the stirring and formation of a vortex lattice from a zero temperature 2D BEC in the presence of quantum noise. In contrast to previous findings, we demonstrated that it is not necessary to break the system symmetry by hand or by numerical integration error in order to realise vortex lattice formation [6].

4. Our earlier work on dynamical instabilities in a BEC in an optical lattice was published [7].

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Atom-atom correlations in colliding Bose-Einstein condensates

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Experiments with colliding Bose-Einstein condensates (BECs) [1, 2] are currently attracting considerable attention in the field of ultra-cold quantum gases. A recent breakthrough in this area is a direct detection [2] of atom-atom pair correlations in the *s*-wave scattering halo formed in the collision of metastable helium (^{4}He*) condensates. Such experimental advances pose increasingly demanding challenges to theory due to the need to provide quantitatively accurate descriptions of the experimental results in realistic parameter regimes.

In collaboration with ACQAO partners at the Institute d'Optique, we have performed first-principles simulations of the quantum dynamics of ^{4}He* BEC collisions and analysed the pair correlations of the scattered atoms [3]. The results are generally in good agreement with the experiment, however, the relatively short simulation durations using the positive-*P* representation method mean that the long time dynamics of the collision dynamics is not yet fully understood. We are currently developing alternative theoretical approaches that can model this behavior.

Additionally, we have developed approximate analytic approaches to the short-time dynamics of atom-atom correlations [4], which give a simple, analytically transparent understanding of the width of the correlation functions. Finally, we are have started to investigate the BEC collision dynamics in a new geometry, in which the collision is taking place in the direction perpendicular to the longitudinal axis of the colliding BECs. This is different to the original experimental configuration of Ref. [2] and gives better detection access to atoms on the *s*-wave scattering halo. The new geometry is also sensitive to detecting Bose enhancement in the direction along the long axis of the condensates. The figure below shows three orthogonal slices of the atomic density distribution in 3D obtained from first principle simulations using the positive-*P* representation method; the directional Bose enhancement can be seen as higher density regions on the scattering shell.

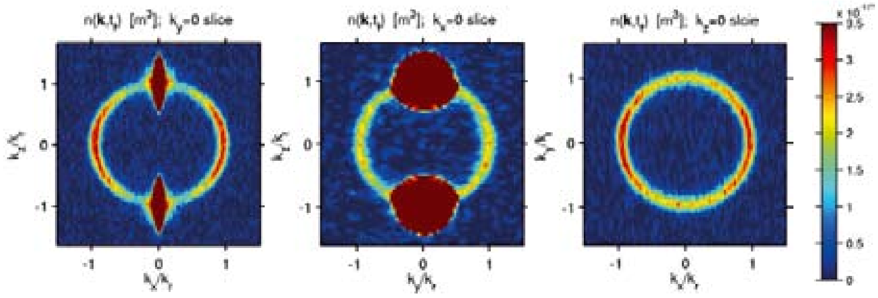

Fig. 1. Three orthogonal slices of the atomic density distribution in momentum space, showing the spherical shell of *s*-wave scattered atoms. The darker regions in the first and second panels (which are off the scale) correspond to the momentum distributions of the two colliding condensates.

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Quantum squeezing with optical fibres: simulations and experiment

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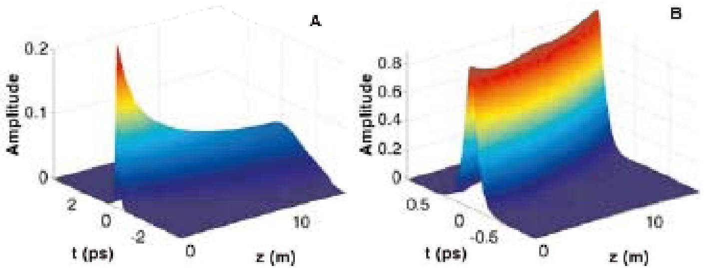
The search for efficient means of quantum squeezing, in which quantum fluctuations in one observable are reduced below the standard quantum limit at the expense of increased fluctuations in the conjugate, has been at the heart of modern developments in quantum optics. The use of optical fibre for quantum squeezing has considerable technological advantages, such as generating squeezing directly at the communications wavelength and use of existing transmission technology. There is, however, a significant disadvantage in the excess phase noise that arises from acoustic waves, molecular vibrations, and defects in the amorphous silica.

We have undertaken an in-depth numerical and experimental study of polarisation squeezing in a single-pass scheme that successfully reduces the impact of this excess phase noise [1]. The numerical simulations represent a quantitative, experimentally testable solution of quantum many-body dynamics. The single-pass setup achieved -6.8 ± 0.3 dB of polarization squeezing, the greatest measured in fibres to date [2]. From known losses, we infer that -10.4 ± 0.8 dB of squeezing was generated in the fibre. Possible improvements in the losses after the fibre, through for example employing more-efficient photodiodes in a minimal detection setup using highest quality optics, may allow measured squeezing in excess of -8 dB.

By analysing the Raman and guided acoustic wave Brillouin scattering (GAWBS) effects in the simulations, we find that the former is a limiting factor for high pulse energies, whereas the latter is detrimental at low energies. Investigation of a range of fibre lengths revealed that greater squeezing is not achieved going beyond 13.2 m. Indeed, simulations indicate that slightly greater squeezing may be achievable at a lower fibre length of around 7 m for the pulse width used (130 fs, FWHM).



Dynamics of optical pulses. (A) A weak pulse disperses before significant squeezing can be acheived and is also affected by GAWBS. (B) Soliton pulses produce the greatest amount of squeezing for a given pulse width. However, at long fibre lengths Raman effects reduce the amount of squeezing achieved.

Further improvement may be possible through the use of photonic crystal fibres (PCF), which have been used in several squeezing experiments. PCFs offer the advantage of higher effective nonlinearities, due to the smaller mode areas that can be achieved, and less GAWBS noise, since there are fewer low-frequency acoustic vibrations. Such an advance would bring fibre-produced squeezed states closer to minimum-uncertainty states

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Delay of squeezing and entanglement with EIT

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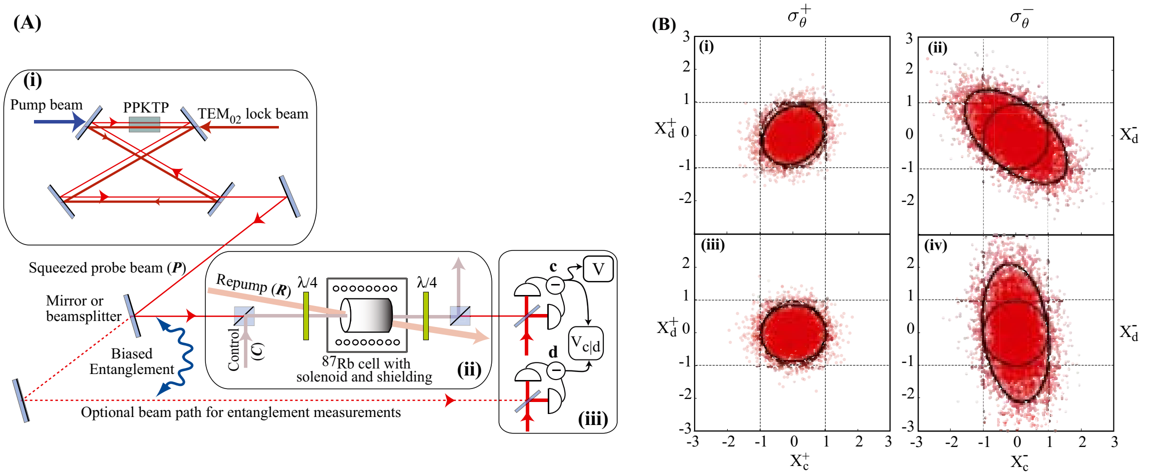
Electromagnetically induced transparency has frequently been suggested as a form of coherent optical memory [1]. In our experiment, we used a hot ^{87}Rb vapour as the EIT medium and a source of squeezed light at 795 nm to generate quantum states that can be be used to test the efficacy of EIT as a coherent delay line.

Our squeezed light source [2] was based on an optical parametric oscillator (OPO) and produced squeezed vacuum states. These were first used in direct transmission through the EIT medium to show squeezed state preservation with EIT. Starting with 3.2 dB of squeezing, we observed preservation of 2 dB at the output of the gas cell [3].

Measuring the delay experienced by the cw squeezed vacuum is very difficult as there is no time reference. In order to make this measurement, we prepared a biased entangled state by splitting our squeezing into 2 beams (Fig. A). Correlation measurements could then be made between homodyne detectors c and d, as shown in Fig. A(iii). Using this technique, and measuring both the amplitude and phase quadratures at the homodyne detectors, showed that half of our biassed entangled state was delayed by 2.2 μs. Furthermore, after the EIT delay we measured the Duan wavefunction separability criterion to be 0.71±0.01. Thus we have shown delay and preservation of entanglement through EIT [3].



A: Schematic of the experiment. (i) Bow-tie PPKTP optical parametric amplifier. The squeezed beam (P) is either injected directly into the EIT setup or divided using a beam-splitter to produce a pair of biased entangled beams. (ii) The gas cell used for EIT. (iii) Joint measurements are performed using two homodyne detectors to analyse the quadrature amplitude correlations. B: Correlation measurements. (i) and (ii): Scatter plots of the amplitude and phase quadratures respectively as measured for the beams c and d. The lasers were not resonant and there is no EIT. (iii) and (iv): Data as above but with EIT switched on. The solid black curves show the conditional deviation $\sigma_\theta^\pm$ calculated from the data. The dashed circles show the QNL conditional deviation obtained by blocking the two entangled paths. The coordinates of the red data points have been scaled down by a factor of two for clarity.

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Dynamical oscillator-cavity model for quantum memories

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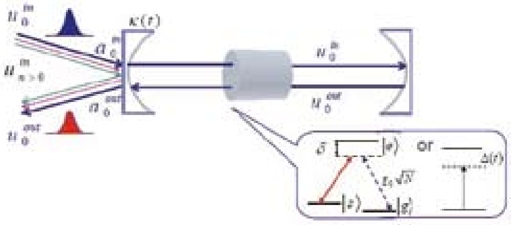
We propose a dynamical approach to quantum memories using an oscillator-cavity model. This overcomes the known difficulties of achieving high quantum input-output fidelity with storage times long compared to the input signal duration.



We use a generic model of the memory response [1], which is applicable to any linear storage medium ranging from a superconducting device to an atomic medium. The temporal switching or gating of the device may either be through a control field changing the coupling, or through a variable detuning approach, as in more recent quantum memory experiments. An exact calculation of the temporal memory response to an external input is carried out. This shows that there is a mode-matching criterion which determines the optimum input and output pulse time-evolution.

This optimum pulse shape can be modified by changing the gate characteristics. In addition, there is a critical coupling between the atoms and the cavity that allows high fidelity in the presence of long storage times. The quantum fidelity is calculated both for the coherent state protocol, and for a completely arbitrary input state with a bounded total photon number. We show how a dynamical quantum memory can surpass the relevant classical memory bound, while retaining long storage times.

Quantum memories are devices that can capture, store, and then replay a quantum state on demand. In principle, storage is not a problem for time-scales even as long as seconds or more, since there are atomic transitions with very long lifetimes that could be used to store quantum states. A quantum memory must store quantum superpositions. These cannot be stored in a classical memory in which a measurement is made on a quantum state prior to storage. The fundamental interest of this type of device is that one can decide at any time to read out the state and perform a measurement. In this way, the collapse of a wave-packet is able to be indefinitely delayed, allowing new tests of decoherence in quantum mechanics.

Such devices also have a fascinating potential for extending the reach of quantum technologies. Here, the main interest is in converting a photonic traveling-wave state - useful in communication - to a static form. Although atomic transitions are normally considered, actually any type of static mode can be used as a quantum memory. For the implementation of quantum networks, quantum cryptography and quantum computing, it is essential to have efficient, long-lived quantum memories. These should be able to output the relevant state on demand at a much later time, with a high fidelity over a required set of input states. The benchmark for a quantum memory is that the average fidelity $\bar{F}$ must be higher than any possible classical memory when averaged over the input states: $\bar{F} > \bar{F}_C$.

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Memory for Light

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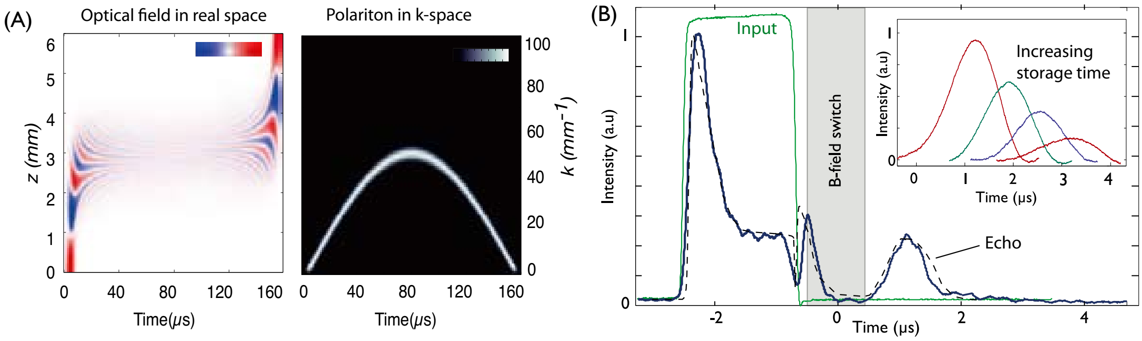
Atoms can be manipulated in different ways so that through interaction with light they can store optical quantum information in a controllable fashion. In order to store quantum information, decoherence processes must be controlled so as to avoid loss through coupling to the environment. High efficiency, fidelity and storage time are some requirements for building a “Quantum Memory”. We have developed a Gradient Echo Memory (GEM) technique that can be used to store quantum information carried by light in coherent ground states of atoms.

Theoretical modelling using two level atoms has shown how the combined atom-light excitation in the GEM system can be described as a normal mode in k-space [1]. The ’speed’ of the normal mode (Fig. A) in the k-t plane can be controlled using the slope of a linearly varying atomic detuning that is applied along the length of the storage medium. This can be done, for example, using a Stark or Zeeman shift. The model also shows that, in the limit of large optical depth, GEM is 100% efficient and preserves the quantum state of the light.

Our experimental implementation of the GEM system is based on a warm gas cell containing ^{87}Rb atoms and buffer gas. By applying a linearly varying magnetic field along the length the atomic ensemble and a strong Raman coupling beam, information can be stored in the ground states of the Rb atoms. By reversing the magnetic field gradient, we observed a photon echo, as shown in Fig. B [2]. So far, efficiency of 5 % has been achieved that is mainly limited by the optical depth of medium. The coherence time of the storage is of the order 1-2 μs. This appears to be mostly limited by Doppler broadening in the gas cells. We anticipate that cold atomic gases may yield great improvements in performance.



A: The optical field decays towards the detuning switching point at 80 μs and then re-grows symmetrically. The polaritonic mode propagates in k-space and reverses direction at the switching point. When the mode reaches the initial k value, light is remitted [1].
B: Storage in a warm rubidium vapour. The input pulse (green) is partially absorbed in the gas cell, the unabsorbed pulse is in blue on the left of the figure. After the magnetic field switch an echo is generated. As the magnetic field flip is delayed, the echo is also delayed, as shown in the inset [2].

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Macroscopic Entanglement between a Superconducting Loop and a Bose Einstein Condensate

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Quantum entanglement is one of the most fundamental and intriguing phenomena in quantum mechanics. We propose an experiment to realise a macroscopic entanglement. A magnetic trap containing a BEC when adiabatically moved close to a superconducting loop existing in quantum superposition of two different flux states [1, 2], can perturb the confining potential of the magnetic trap leading to a macroscopic entanglement [3]. The macroscopic variables correspond to the spatial distribution of the BEC in the trap, the chemical potential and the flux state of the superconducting loop. A schematic of the superconducting loop coupled to a magnetic trap is shown in Fig. 1. In addition, we also explore the effect of a sudden turn on of the coupling between the superconducting loop and the magnetic trap.

The Hamiltonian of the superconducting loop coupled with the magnetic trap can be written as

$$H(t) = E_0|0\rangle\langle 0| + E_0|1\rangle\langle 1| + \mu_0 \hat{a}_0^\dagger \hat{a}_0 |0\rangle\langle 0| + \mu_1 \hat{a}_1^\dagger \hat{a}_1 |1\rangle\langle 1| \tag{1}$$

where $|0\rangle$ and $|1\rangle$ corresponds to the flux state of the loop, $\hat{a}_0$ ($\hat{a}_1$) is the bosonic annihilation operator when the trap potential is perturbed by the state $|0\rangle$ ($|1\rangle$).

Considering the initial state $|\Psi, t=0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)|N, \phi(r, t=0)\rangle$, where $|N, \phi(r, t=0)\rangle$ is the state representing N atoms in the ground state of the trap when the perturbation caused by the loop is zero. At time t the state evolves to an macroscopic entangled state

$$|\Psi, t\rangle = \frac{1}{\sqrt{2}}(|0\rangle|N, \phi_0(r,t)\rangle + e^{i\Phi(t)}|1\rangle|N, \phi_1(r,t)\rangle) \tag{2}$$

where $|N, \phi_0(r,t)\rangle$ and $|N, \phi_1(r,t)\rangle$ correspond to N atoms in the ground state of two different perturbed potentials introduced by the loop.

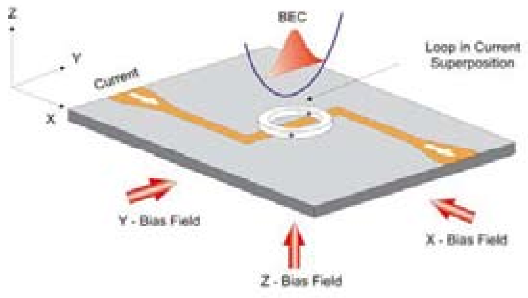

Fig. 1: Schematic of an atom chip containing the superconducting loop.

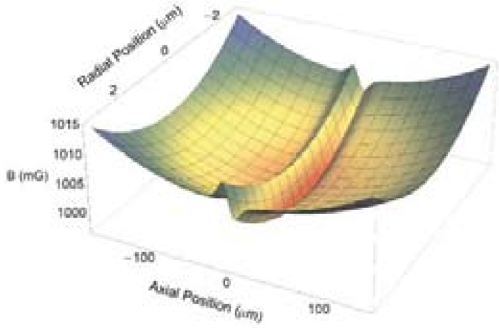

Fig. 2: Perturbation induced in the magnetic trap by the loop in state $|0\rangle$.

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Thermodynamics and nonlocal pair correlations in 1D Bose gases

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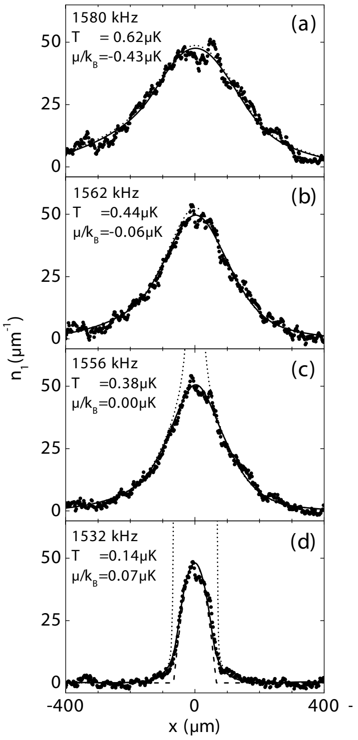
Reducing the dimensionality of a quantum system can have dramatic consequences. For example, the 1D Bose gas with repulsive δ-function interactions exhibits a surprisingly rich variety of physical regimes that is not present in 2D or 3D. The 1D Bose gas model is of particular interest because exact solutions for the many-body eigenstates can be obtained using a Bethe ansatz [1]. Furthermore, the finite-temperature equilibrium can be studied using the Yang-Yang (YY) thermodynamic formalism [2]. The experimental achievement of ultracold atomic Bose gases in the 1D regime has attracted renewed attention to the 1D Bose gas problem and is providing previously unattainable opportunities to test the YY thermodynamics. In 2008, we have made progress on several fronts in the study of 1D Bose gases.

We have established a collaboration with the van Druten group in Amsterdam who have been studying the thermodynamics of 1D Bose gases. They have made measurements of the density profiles of their system over a range of temperatures, and we have shown [3] that the measured density profiles are very well described by a model based on exact solutions obtained using the YY thermodynamic formalism. The figure on the right shows the linear (1D) atomic density obtained from *in situ* absorption images at different temperatures (T) and chemical potentials (μ). Solid lines are fits using YY thermodynamic solutions. Dotted lines are the ideal Bose gas density profiles showing divergence for $\mu(x) = 0$. Dashed line in (d) is a quasi-condensate density profile with the same peak density as the experimental data.



In collaboration with Raizen's experimental group (University of Texas, Austin) and D. M Gangardt (University of Birmingham), we have analytically calculated the spatial nonlocal pair correlation function for a uniform 1D Bose gas at finite T [4]. The summary of the results is given in the ACQAO Annual Reports for 2007. We are currently combining these results with the numerical calculation of the pair correlation function in the crossover regimes where the analytic approaches do not work [5].

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Superfluidity and thermodynamics of low-dimensional Bose gases

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Degenerate Bose gas systems in one and two dimensions have many differences to standard Bose-Einstein condensates in three dimensions, and are now beginning to be realised in the laboratory [1, 2]. It is important to be able to apply our theoretical techniques to make predictions for realistic experimental systems, or to analyze existing experimental data and interpret these results from a theoretical viewpoint.

1. Recent experiments by the ENS group and the NIST-Gaithersburg group have probed the existence of the superfluid Berezinskii-Kosterlitz-Thouless (BKT) phase in 2D Bose gas systems [1, 2]. We have been studying a size-matched homogeneous system using classical field methods in order to study the behaviour of vortex pairs, and to develop an understanding of the relationship between BEC and BKT phases in a finite-size system. We have also studied the emergence of bimodality, coherence, and superfluidity in the trapped 2D system in order to try to reconcil a number of different pieces of experimental data [5]. Work on evidence of superfluidity in this system was published this year [6].

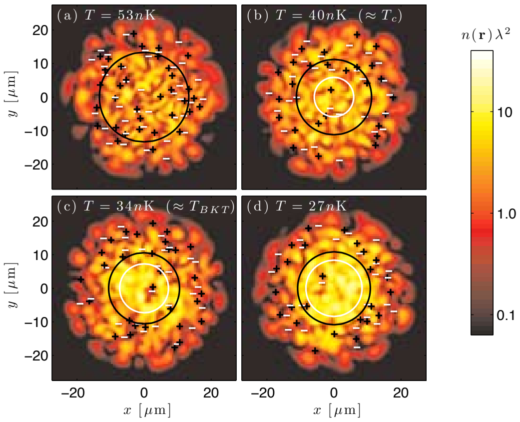

Fig. 1: Regimes of quantum degeneracy (BEC and BKT phases) in a 2D Bose gas.

2. Using perturbation theory, it has been suggested that quantum fluctuations in 3D BECs in an infinite system can cause a non-zero drag force on an object in a flow at all velocities [3], in contradiction with our conventional understanding of superfluidity. We have been working on this calculation for a one-dimensional system, which has the advantage that much of it can be done analytically [4]. It is also feasible to numerically simulate this system, and we have begun calculations aimed at conclusively demonstrating this force numerically in a finite system.

3. We have continued a collaboration with the van Druten group in Amsterdam who have been studying the thermodynamics of the 1D Bose gas. They have made measurements of the density profiles of their system over a range of temperatures, and we have fit these using the Yang-Yang thermodynamic solution for the 1D Bose gas in the local density approximation [7]. They have also measured the momentum distribution which cannot be computed using the Yang-Yang solution, and we are trying to do so using classical field methods.

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Negative group velocity in a coherence-free cold atomic medium

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We have observed superluminal propagation of a light pulse through an atomic medium in which the fast light arises from the intrinsic anomalous dispersion associated with an atomic absorption line. Steep dispersion is associated with narrow absorption resonances, and fast light conditions in atomic media have most often been achieved by exploiting very narrow ground-state coherence resonances. However, in this work our aim has been to demonstrate fast light in a coherence-free medium, using the anomalous dispersion that results from linear atom-light interaction. Such a simple system should aid understanding of the underlying mechanism responsible for superluminal propagation which remains a subject of some debate despite its apparent phenomenological simplicity.

The pulse advance was observed in a cloud of cold ^{85}Rb atoms in a magneto-optical trap. The atomic medium was first characterized using a radiofrequency heterodyne technique [1] in which a bichromatic beam with frequency components offset by typically 80 MHz is split so that one bichromatic beam passes through the atomic medium while the other does not. The output of a radiofrequency mixer, in which the two beat signals are combined, depends on the optical phase shift experienced by either frequency component as it is scanned through an atomic resonance.

To observe the pulse advance directly, an AOM was used to generate a 35 ns-long optical pulse (Fig.1a) which propagated through the MOT [2]. The frequency of the light was tuned to the transmission minimum on the $5S_{1/2}(F=3) \rightarrow 5P_{3/2}(F=4)$ transition, where the rf heterodyne technique indicated a spectral region of up to 40 MHz of negative and constant dispersion. This places a lower limit on the pulse lengths that can be used, and is an order of magnitude wider than that typically associated with ground-state coherences. Although it is well established that fractional advance of a light pulse is harder to achieve than the same fractional delay, the observed pulse advance of 3.6 ns relative to an off-resonant control pulse (Fig.1b) represents a significant fractional advance of around 10% for a pulse attenuated by approximately 50%, and corresponds to a negative group velocity $-c/360$, in good agreement with the value of anomalous dispersion of $dn/d\nu \approx -1.3\times10^{-12}$ Hz^{-1} determined with the rf heterodyne technique.

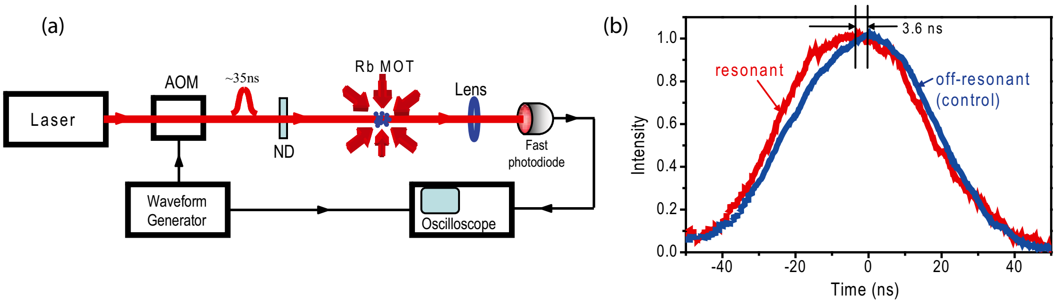

Fig. 1: (a) Experimental arrangement for observing pulse advance. (b) Normalised resonant and off-resonant pulses after propagation through the ^{85}Rb MOT. The linearly polarised probe was resonant with the $5S_{1/2}(F=3) \rightarrow 5P_{3/2}(F=4)$ transition. Attenuation of the resonant pulse is less than 50%

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Single Atom Detection With Optical Cavities

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Single neutral atoms have been observed and counted using a variety of techniques. For metastable atoms in highly excited states, such as metastable helium or neon, the internal atomic energy can be used to eject electrons from a metal surface on impact. The electron pulse can be accelerated and detected with good signal-to-noise ratio (SNR) allowing single atom counting. Neutral ground-state atoms do not have enough energy for this process. Instead, common detection techniques exploit the interaction of the atom with light. Single atoms have been observed with fluorescence detection, and by measuring the effect on the field in optical cavities, as shown in Fig. 1(A). For the most part, however, optical cavity experiments and theory have concentrated on obtaining strong atom-light coupling for cavity QED demonstrations. In this work [1], we concentrated on two questions: 1) do we need cavities of extreme finesse to achieve effective single atom detection; and 2) what is the best regime to work in with respect to probe power as well as optical and atomic frequency detunings?

Using the steady state solution to the quantum master equation for the atom-cavity system, we modelled the expected optical field inside the cavity and translated this into a signal-to-noise ratio for atom detection when monitoring the power of the transmitted cavity field. Our model was scanned over a wide range of atom-light frequency detunings, light-cavity detunings, probe power and cavity finesse. Our results show that, although the signal-to-noise of atom detection improves with finesse, as shown in Fig. 1(B), even a moderate value of 10,000 is sufficient to obtain very good atom detection provided one is able to use higher probe power. This eliminates APDs as suitable detectors, but heterodyne detection is shown to be quite suitable. In fact, a very high finesse cavity (~300,000) with an APD detection scheme is predicted to have similar detection characteristics to a 10,000 finesse cavity with heterodyne detection. Furthermore, it was shown that large atomic detuning, which can also be useful to control atom trajectories via the dipole force, can also yield high signal-to-noise ratios (Fig. 1(C)).

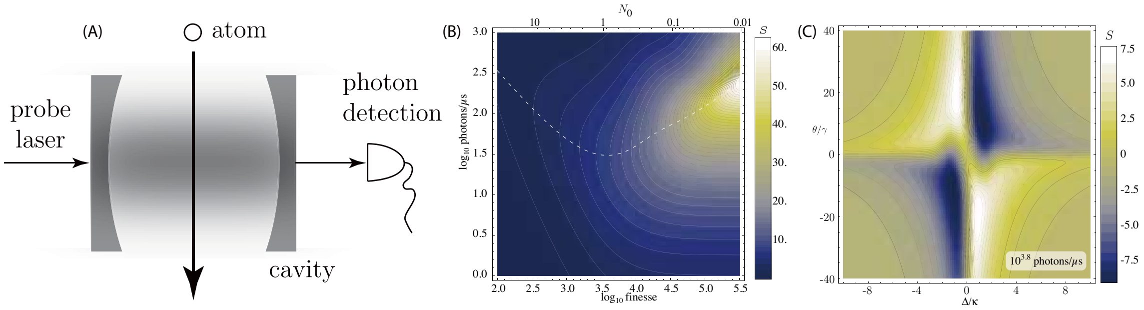

Fig. 1: Single atom detection with an optical cavity showing (A) schematic diagram of cavity set-up; (B) signal-to-noise ratio for atom detection as a function of finesse and power for a resonant atom cavity system and (C) signal-to-noise ratio as a function of atomic and optical detunings for fixed power and finesse of 10,000.

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p-wave Feshbach molecules

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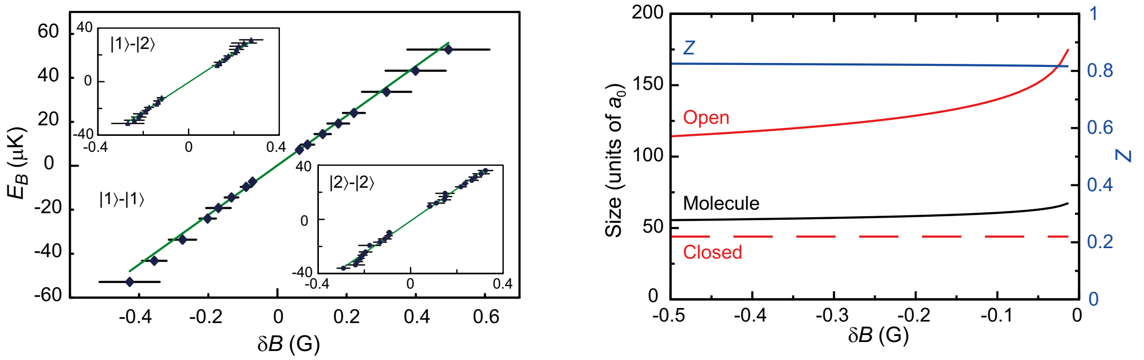
Ultracold gases of fermionic atoms near a Feshbach resonance offer an ideal setting to study pairing and superfluidity. The majority of work to date has focussed on gases near s-wave Feshbach resonances in which the interatomic scattering is isotropic. Higher order scattering processes involving nonzero angular momentum are generally suppressed in cold gases as particles do not have the energy to overcome the centrifugal barrier. Near a Feshbach resonance, however, this barrier can be overcome and strong higher order scattering and pairing can occur.

We have studied a gas of ultracold ^{6}Li near the three p-wave Feshbach resonances in a mixture of the states $|F = 1/2, m_F = +1/2\rangle$ ($|1\rangle$) and $|1/2, -1/2\rangle$ ($|2\rangle$). We have produced p-wave molecules and measured their binding energies using radio frequency (rf) magneto-association spectroscopy for all three resonances. The binding energy increases linearly with magnetic field detuning and our measured values of $113 \pm 7\,\mu$K/G, $111 \pm 6\,\mu$K/G and $118 \pm 8\,\mu$K/G for the $|1\rangle$-$|1\rangle$, $|1\rangle$-$|2\rangle$ and $|2\rangle$-$|2\rangle$ resonances, respectively, are in good agreement with theoretical predictions for the magnetic moments of the molecules. Figure 1(a) below shows the binding energy measurements for the $|1\rangle$-$|1\rangle$ resonance with a linear fit (insets show the two other resonances) [1].

In our experiments the lifetime of these molecules was limited to a few ms via inelastic collisions with unpaired atoms. The small size of the molecules and large closed channel fraction, Fig. 1(b), is in stark contrast with typical s-wave molecules and means that the Pauli suppression mechanism responsible for the long lifetimes of s-wave molecules does not apply. It may, however, be possible to extend the molecular lifetime in lower dimensional settings which we are currently investigating.



(a) (b)

Fig. 1: a) Binding energies of ^{6}Li p-wave Feshbach molecules vs magnetic field detuning. (b) Calculated closed channel fraction (Z), molecule size and size of the open and closed channel components for p-wave molecules below the $|1\rangle$-$|1\rangle$ resonance.

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Quantum-atom optics using dissociation of molecular condensates

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Dissociation of a Bose-Einstein condensate (BEC) of molecular dimers into pair-correlated atoms represents the matter-wave analog of two-photon parametric down-conversion. The latter process was of crucial importance to the development of quantum optics. Through this analogy, molecular dissociation currently represents one of the "workhorses" of *quantum-atom optics* and offers promising opportunities for the generation of strongly correlated atomic ensembles and fundamental tests of quantum mechanics with macroscopic numbers of massive particles.

We have studied atom-atom correlations and relative number squeezing in the dissociation of a BEC of molecular dimers made of either bosonic or fermionic atom pairs. Our treatment addresses the effect of the spatial inhomogeneity of the molecular BEC on the strength of correlations in the short-time limit [1]. In the undepleted molecular field approximation, we obtain explicit analytic results for the density-density correlation functions in momentum space (see Fig. 1), and show that the correlation widths and the degree of squeezing are determined predominantly by the shape of the molecular BEC (see Fig. 2). The results show how improved squeezing is obtained with larger condensates, and how it is degraded in strongly inhomogeneous systems.

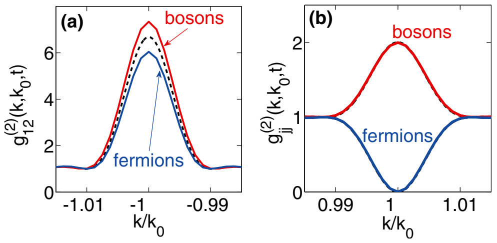

Fig. 1. Back-to-back (BB) (a) and collinear (CL) (b) correlation $g^{(2)}_{ij}(k,k_0,t)$ as a function of the momentum k at time $t/t_0 = 0.5$, where $t_0 = 1/\chi\sqrt{\rho_0(0)} \simeq 5$ ms; the Thomas-Fermi radius of the molecular BEC is $R_{\rm TF} = 250\ \mu$m. The solid lines are the numerical results; the dashed lines are the short-time analytic results.

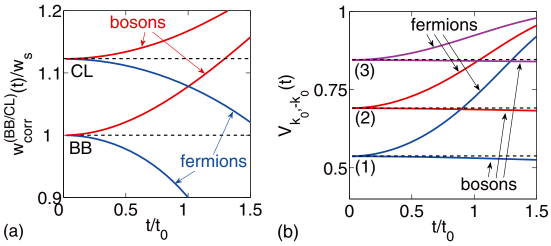

Fig. 2. (a) Width of the BB and CL correlation in units of the momentum width of the molecular BEC, $w_s \simeq 1.62/R_{\rm TF}$, as a function of time. (b) Relative number variance $V_{k_0,-k_0}(t)$ as a function of time, for $R^{(1)}_{\rm TF} = 250\ \mu$m (1), $R^{(2)}_{\rm TF} = 167\ \mu$m (2), and $R^{(3)}_{\rm TF} = 83\ \mu$m (3). The counting length is $\Delta k = \pi/2R^{(1)}_{\rm TF}$ in all cases.

In order to treat the molecular depletion, we have developed a pairing-mean field theory for the dynamics of dissociation for the uniform case [2]. The summary is given in ACQAO annual report for 2007. We are currently extending this method to nonuniform systems [3], and making a comparative analysis of the performance of different theoretical techniques for dissociation dynamics, including the truncated Wigner method, the positive-P representation for bosons, and a Gaussian stochastic method for fermions [4]. Finally, we have analysed the dissociation of elongated molecular condensates in highly anisotropic trapping potentials and have shown that it can produce qualitatively different geometrical distributions for bosonic and fermionic atoms [5].

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Bragg spectroscopy of a strongly interacting Fermi gas

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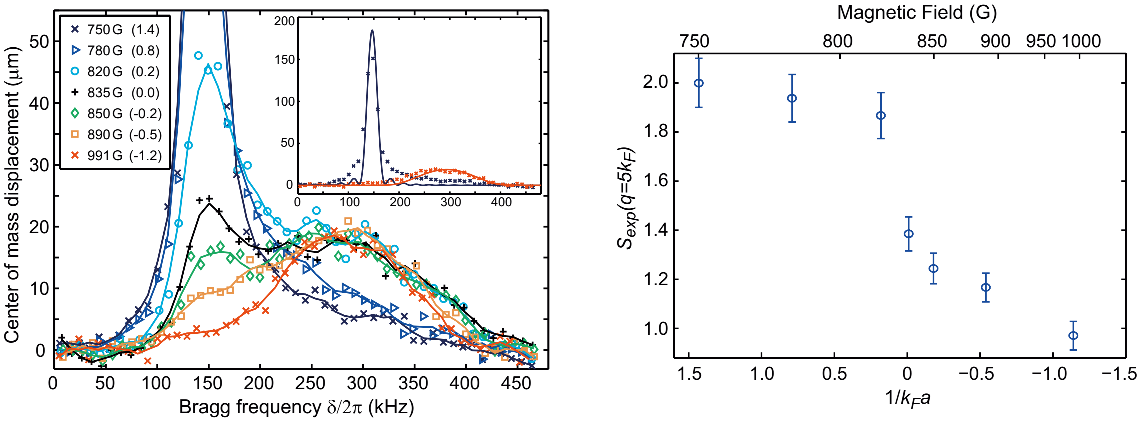
Strongly interacting ultracold Fermi gases provide new opportunities for the study of pairing and superfluidity. The ability to precisely tune the interactions between fermions in different spin states using a magnetic field Feshbach resonance has led to the realisation of long lived condensates of paired fermionic atoms in the molecular Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) crossover. We have used Bragg spectroscopy to study this crossover at the broad s-wave Feshbach resonance at 834 G in fermionic ^{6}Li.

Figure 1(a) shows Bragg spectra obtained at various magnetic fields across the Feshbach resonance. These spectra reflect the composition of the gas, being dominated by bosonic molecules below the Feshbach resonance, pairs and free fermionic atoms near unitarity, and free fermions above resonance. Integrating these spectra over the Bragg frequency gives a number proportional to the static structure factor, $S(q)$, where $q \approx 5k_F$ in our experiments (k_F is the Fermi wavevector). In figure 1(b) we plot the integral of the Bragg spectra, normalised so that $S(q) = 2$ in the molecular limit. $S(q)$ decays monotonically from 2 to 1 over the BEC-BCS crossover due to the decay of spin up/spin down correlations [1].



(a) (b)

Fig. 1: a) Bragg spectra of a Fermi gas across the BEC-BCS crossover at magnetic fields $(1/k_F a)$ given in the legend. Inset shows the 750 G and 991 G spectra along with the calculated response for an ideal Fermi gas and molecular BEC. (b) Experimental static structure factor $S_{exp}(q = 5k_F)$ vs. the scaled interaction parameter $1/k_F a$ and magnetic field.

We have also investigated the density dependence of pairing in these gases using Bragg scattering and have been able to distinguish true bound molecules from many-body pairs which occur only in trapped strongly interacting systems [1].

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Strongly Interacting Fermi Gases

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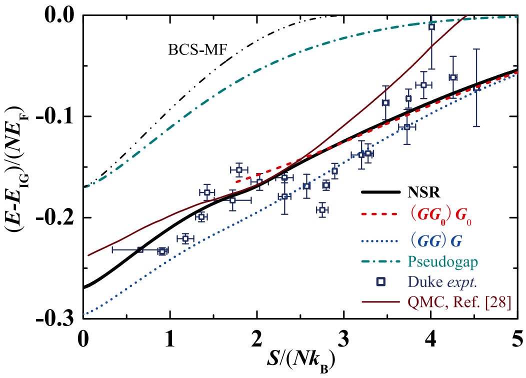
Strongly interacting Fermi gases are of great interest. Interacting fermions are involved in some of the most important unanswered questions in condensed matter physics, nuclear physics, astrophysics, and cosmology. In 2008, we presented a systematic comparison of strong-coupling theories, predicted the finite-temperature phase diagram of a polarized system and investigated the collective modes in multicomponent attractive Fermi gas[1-4].

Comparative study of strong-coupling theories In the strongly interacting regime the main theoretical difficulty lies in the absence of any small coupling parameter, which is crucial for estimating the errors of approximate approaches.



In the paper [1], using experimental data as a benchmark, we present an unbiased test of several strong-coupling theories that are commonly used in the literature, including QMC simulations. From this comparison, we show the simplest theory, our below-threshold version of the Nozieres and Schmitt-Rink treatment, which incorporates pairing fluctuations, appears to be quantitatively accurate at unitarity. We find it describes the observed thermodynamics extremely well at all temperatures at unitarity, except near the superfluid transition temperature. Some earlier theories clearly fail completely.

Polarized Fermi gases Recently, two experimental groups at MIT and Rice University have successfully created a two-component atomic Fermi gas with unequal spin populations. This type of matter is of great interest, and has stimulated intense efforts towards studying this unsolved theoretical problem in condensed matter and particle physics. Motivated by these experiments, we have investigated the properties of an ultracold atomic Fermi gas with spin population imbalance in a quasi-one-dimentional trap [3]. Our exact results are being tested by an ongoing experiment at Rice University which is searching for the predicted exotic, spatially modulated or FFLO states in a highly elongated harmonic trap.

Multicomponent Fermi gases Recent advances in ultracold atomic Fermi gases make it possible to achieve a fermionic superfluid with multiple spin components. In this context, any mean-field description is expected to fail, owing to the presence of tightly bound clusters or molecules that consist of more than two particles. By using the exact Bethe ansatz solution and a local density approximation treatment of the harmonic trap, we have investigated the equation of state of a multicomponent Fermi gas [4]. We show that there is a peak in the collective mode frequency at the critical density for a deconfining transition to many-body state that is analogous to the quark matter color superconductor state expected in neutron star interiors.

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Quantum dynamics of ultracold atoms in double wells

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Ultracold atoms in a double-well are one of the simplest systems in which to probe quantum many-body physics. Nevertheless, the system contains some very rich physics, including quantum coherence, Josephson effects, localisation, squeezing and entanglement. Furthermore, as it has the basic form of an interferometer, the double well is an important system for possible precision measurement with ultracold atoms. Here, we summarize four different projects that are investigating quantum dynamics of bosons and fermions in a double-well potential.

The first two projects explore the behaviour of small condensates in a double-well potential, using a two-mode approximation and a number state analysis. For the case of repulsive interactions, the squeezed ground state has been suggested to achieve precision measurement beyond the standard quantum limit [1]. We have investigated the nonlinear effects of residual interactions during the course of the measurement, finding that they do have a detrimental effect on the precision. We have also proposed and tested schemes to overcome these nonlinear effects over a range of interaction strengths. For the case of attractive interactions in double-well condensate, it may be possible to dynamically create a macroscopic superposition state by making use of the Feshbach resonance. We have considered various measurements aimed at distinguishing a superposition state from a statistical mixture, including quadrature phase measurements and atom number measurements after a short tunelling time. We have found that both these sets of measurements would require very accurate atom counting to successfully distinguish between a coherent superposition and a statistical mixture of states. For the quadrature phase measurements, successfully detecting a superposition state may increase in difficulty with the number of atoms involved in the state, due to a narrowing of the expected interference fringes. In the third project, we go beyond the two-mode model, using a fully 3D spatial Bogoliubov approach to the two well systems, to analyse the number squeezing and compare it to experiments at Heidelberg [2].

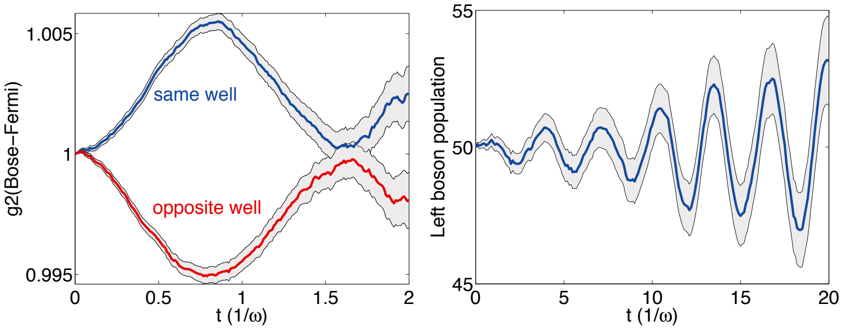

Fig. 1: Dynamics of Bose-Fermi mixtures in a double-well potential. Left: nonclassical correlations develop as a result of Bose-Fermi repulsion. Right: fermion imbalance causes oscillations to develop in Boson population.

Finally, we have used the double-well system to test novel phase-space simulation methods for the quantum dynamics of fermions. The simulation methods are based on a generalised Gaussian representation of the quantum density matrix and have previously been used to calculate the ground-state properties of the repulsive Hubbard model. Here, we focus on real-time quantum dynamics, and Bose-Fermi mixture in particular. Preliminary work shows that the Gaussian method is able to simulate tunnelling dynamics in situations where significant beyond-mean-field correlations develop.

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Many-body quantum physics of Josephson coupled Bose condensates

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Atomic Bose-Einstein condensates are intrinsic many-body quantum systems. Many-body quantum effects become significant in low-dimensional systems and systems with strict symmetry constraints, degeneracy, or strong interaction. Examples include low-dimensional quantum gases, spinor condensates, rapidly rotating systems, strongly interacting systems, and condensed atoms loaded into deep multi-well potentials. For condensates confined in multi-well potentials, such as double-well potentials and optical lattices, the Josephson tunneling links together the condensates in different wells and then establishes the relative phase which could be measured in experiments.

By loading condensates into magnetic or optical double-well potentials, atomic interferometers have been demonstrated in several labs [1, 2, 3, 4], including the SUT node of ACQAO. Beyond the macroscopic quantum coherence, various many-body quantum effects such as coherence fluctuations, conditional tunneling, squeezing, and entanglement have been observed in experiments, and applications of these effects in modern quantum technology such as high-precision measurement [5] and quantum information processing have been discussed. Recently, we gave clear theoretical explanations for the full picture of the coherence fluctuations, the resonant tunneling and the interaction blockade [6].

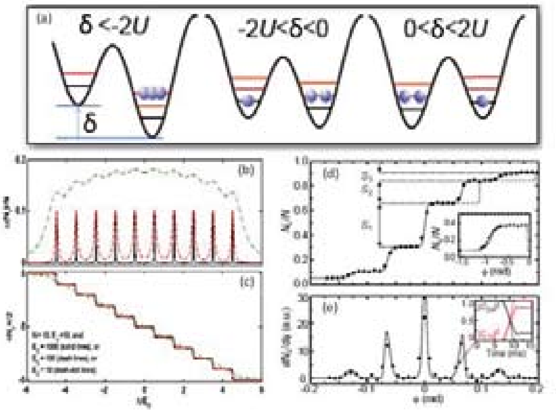

Fig. 1: Resonant tunneling and interaction blockade. (a) The schematic diagram, (b) and (c) Our theoretical prediction [6], (d) and (e) Experimental data from Bloch's group [7].

We introduce universal operators for characterizing many-body coherence without limitations on the system symmetry and total particle number N. We not only reproduce the results for both coherence fluctuations and number squeezing in symmetric systems of large N, but also reveal several peculiar phenomena that may occur in asymmetric systems and systems of small N. For asymmetric systems, we show that, due to an interplay between asymmetry and inter-particle interaction, the resonant tunneling and interaction blockade take place in sequence. The resonant tunneling and interaction blockade have been confirmed in Bloch's lab [7], and they may be used for counting atom numbers and creating single-atom devices with promising technology applications.

Our most recent studies deal with both mean-field and full quantum dynamics of symmetry-breaking transitions in Josephson coupled condensates. In particular, we explore the universal dynamical mechanisms and anomalous mean-field breakdown induced by symmetry breaking [8].

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Phase evolution in a two-component Bose-Einstein condensate

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Precision measurements and accurate knowledge of the matter wave phase are critical factors in interferometric measurements of a parameter. We study the spatial evolution of a two-component Bose-Einstein condensate and carry out relative phase measurements using a coherent superposition of the states $|F=1, m_F=-1\rangle$ and $|F=2, m_F=+1\rangle$ in a ^{87}Rb condensate generated on an atom chip [1]. Using a Ramsey interferometer scheme we prepare a phase-coherent two-component system with a π/2 two-photon microwave-radiofrequency pulse and probe the dynamical evolution of the system using the second state-mixing π/2 pulse with a variable time delay. The inter- and intra-species scattering lengths have slightly different values and, as a result, the first π/2 pulse prepares the system in a non-equilibrium and evolving state [2]. We measure the two-dimensional distribution of the column densities of each component along the axial and radial coordinates after a short time-of-flight expansion of the condensate before (n_1 and n_2) and after ($n_1^{'}$ and $n_2^{'}$) the application of the second π/2 pulse (Fig. 1). The spatial dependence of the relative phase can be extrapolated using the equation

$$\sin[\phi_2(x)-\phi_1(x)] = \frac{n_2^{'}(x)-n_1^{'}(x)}{2\sqrt{n_1(x)n_2(x)}}. \quad (1)$$

Our preliminary results [3] clearly demonstrate a non-uniform spatial growth of the relative phase along the axial direction of the microtrap and are in excellent agreement with the results of our modelling of the non-equilibrium dynamics using the three-dimensional numerical solution of coupled Gross-Pitaevskii equations.

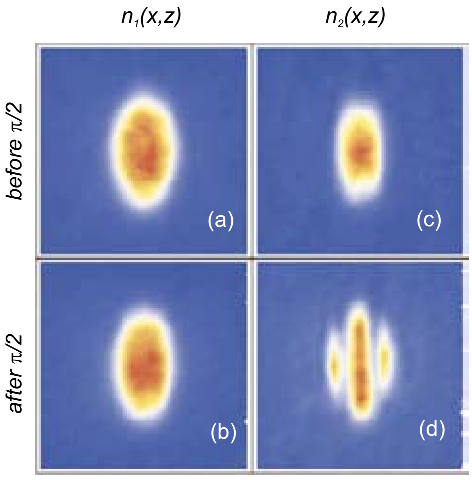

Fig. 1: Two-dimensional distribution of the column density of rubidium atoms in the state $|1\rangle = |F=1, m_F=-1\rangle$ (a and b) and the state $|2\rangle = |F=2, m_F=+1\rangle$ (c and d) along the axial (x) and radial (z) coordinates before and after the second π/2 pulse (the 40 ms delay after the first pulse). Interference fringes are clearly present in the state $|2\rangle$ (d) and are the result of the spatial dependence of the relative phase.

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Spin-domain and vortex formation in antiferromagnetic BECs

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Spin degrees of freedom in atomic condensates open up possibilities for new phenomena such as spin waves, spontaneous magnetization, and spin mixing. However, perhaps the most intriguing effect is associated with complex patterns, such as spin textures or domains, which may appear either as stationary low-energy states or emerge spontaneously due to condensate instabilities. Pattern formation is a common feature in the dynamics of extended nonlinear systems ranging from optics to fluids. Such patterns often develop through the exponential growth of unstable spatial modulations, known as modulational instability. In the spinor condensates, we have the opportunity to examine such effects in an environment which is remarkably easy to control and manipulate through an external magnetic field.

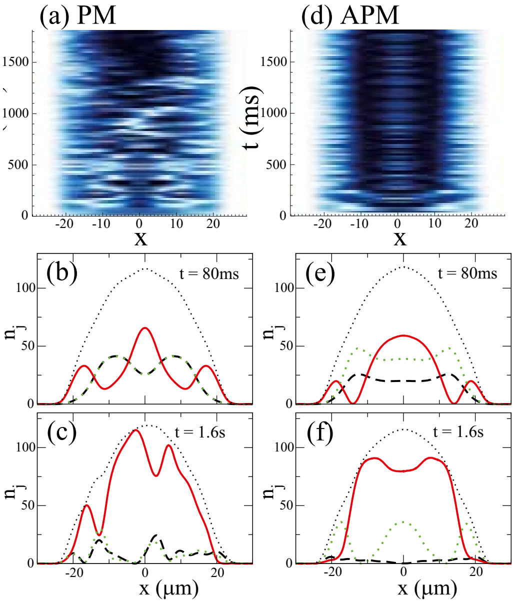

Fig. 1: Spin-domain formation in a sodium condensate confined in an optical harmonic trap. (a,d) - Evolution of the spin-0 component; (b-f) - densities of all three condensate components at the given times. Dotted lines show total density.

The evolution of a dilute spin-1 Bose–Einstein condensate can be, under certain assumptions, described by coupled Gross–Pitaevskii (GP) equations. The spin–dependent interaction coefficient c_2 is negative for ferromagnetic, and positive for antiferromagnetic condensates. Antiferromagnetic (or polar) condensates are generally believed not to display modulational instability or spin domain formation. We reveal that, in fact, a weak homogeneous magnetic field (175 mG) leads to spin domain formation in antiferromagnetic condensates, provided the condensate is larger than the spin healing length. Furthermore, we show that this spin domain formation is initiated by a new type of modulational instability, reminiscent of instabilities observed in nonlinear optics [1] and not seen before in Bose-Einstein condensates. While spin-domain formation in antiferromagnetic condensates has been observed before in the presence of a magnetic field gradient [2], we show that it occurs equally well in the presence of a homogeneous magnetic field [3].

Within the framework of the GP model, we attribute this instability to the appearance of imaginary frequencies of the Bogoliubov modes, which is physically linked to the distribution of spin energy per atom in different spin states. Furthermore, the spontaneous spin-domain formation is associated with stationary states of the condensate which exist in the presence of a weak magnetic field, and which intrinsically break the validity of the single-mode approximation. Our analysis suggests that this novel effect can be observed in sodium condensates confined in an elongated optical trap The initial state is the the $m = -1$ component in the ground state of harmonic trap and the noise corresponding to quantum or thermal fluctuations. After 150 ms of evolution, we see that the instability develops into randomly placed vortices and spin domains (see Figure 1).

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Magnetic phase transitions in 1D spinor Fermi gases

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Atomic Fermi gases with internal spin degrees of freedom are tunable interacting many-body quantum systems featuring novel and subtle magnetic phase transitions. Recent experimental efforts on two-component Fermi atomic gases have explored the quantum phase transition between BCS superfluid and normal Fermi liquid. These experiments have revived interest in one-dimensional (1D) integrable model of multi-component fermions.

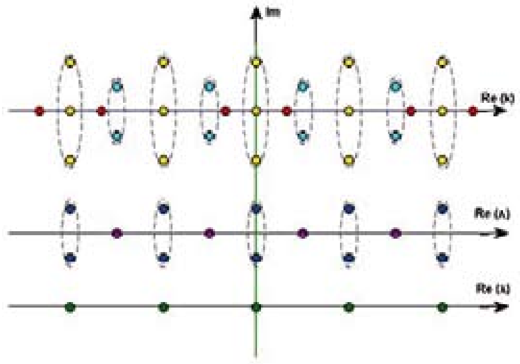

Fig. 1: Schematic configuration of Bethe ansatz quasimomenta k, spin momenta Λ, and λ in the complex plane. For strongly attractive interaction, the unpaired and paired quasimomenta can penetrate into the central region occupied by trions.

More spin degrees of freedom involve more complex symmetries and will reveal more exotic features, such as color superfluid and baryonic phase. Three-component Fermi gases may exhibit $SU(3)$ symmetry and support novel color superfluid of three different types of BCS pairs. In particular, strongly attractive atom-atom interaction in a three-component system can cause the appearance of spin neutral three-body bound states called *trions*. Therefore, magnetic phase transitions are expected to occur between color superfluids and trionic phases. The $N-$component systems could display a group chain $SU(N) \supset SU(N-1) \supset \cdots SU(2) \supset U(1)$ symmetries associated, correspondingly, with exotic quantum phases of the N-body bound states, $(N-1)$-body bound states, $\cdots$, BCS pairs, and normal Fermi liquid.

In recent years, we developed an exact analytical method for 1D many-body quantum systems based upon the Behte ansatz (BA). With this method, we have not only studied Bose gases in a 1D hard-wall box [1], but have also investigated both, two- [2] and multi-component [3, 4] 1D spinor Fermi gases. Most recently, by solving the BA equations and the equations for corresponding dressed energies, we explored the precise nature of all bound states, and calculated critical fields and the full phase diagram. These results provide useful benchmarks for experiments with ultracold spinor fermions. A three-component system, arising from Zeeman splitting [3], shows exotic phases of trions, BCS pairs, a normal Fermi liquid, and four mixtures of these states. In particular, a smooth phase transition from a trionic to pairing phase occurs as the highest hyperfine level separates from the two lower energy levels. In contrast, a smooth transition from the trionic phase into the normal Fermi liquid occurs as the lowest level separates from the two higher levels.

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Dynamics of matter-wave solitons in a ratchet potential

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The ratchet effect, i.e. rectified average current induced by an asymmetric potential and unbiased zero-mean driving force, has been extensively studied in various physical contexts due to its relevance to biological systems and nanotechnology [1]. The theory predicts that, in order for a ratchet to work, the space-time symmetry of the driving potential should be broken and the experiments with cold atoms and Bose-Einstein condensates (BECs) in optical ratchet potentials (see, e.g., [2]) have confirmed this prediction. These experimental advances coincide with the growing interest in the effect of interaction on ratchet transport. As a physical system with intrinsically present nonlinear interactions due to atomic scattering, a BEC supports the existence of spatially localized, particle-like collective excitations - *matter-wave solitons*. It is therefore natural to consider the possibility that a ratchet potential can not only provide the means to transport the condensate bulk, but also to control a directed motion of individual matter-wave solitons.

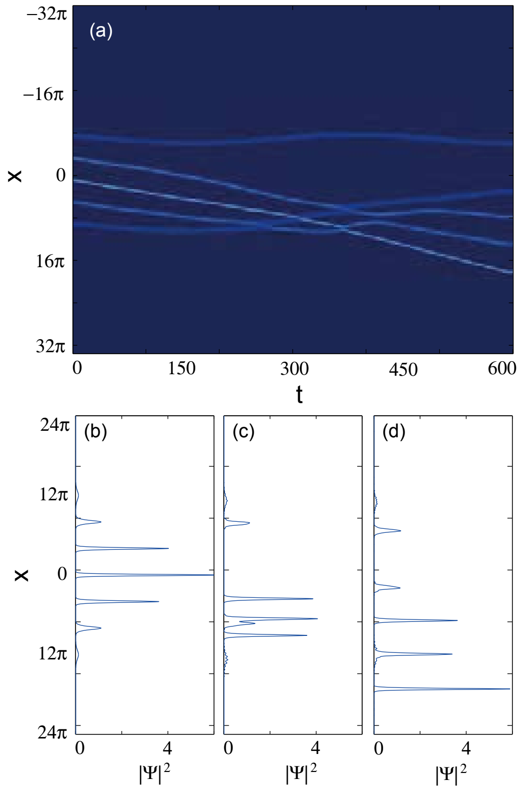

Fig. 1: Dynamics of an array of bright solitons in a ratchet potential. Larger solitons move faster, which results in spatial separation of solitons with different masses.

Recently we have studied the dynamics and transport of bright matter-wave solitons in a weak flashing optical ratchet potential [3, 4]. The important feature of the ratchet-induced transport is the dependence of the soliton cumulative velocity on both number of atoms and the initial position of the soliton. For small atom numbers, the soliton transport occurs in one direction only, while larger solitons may be transported in either direction. As a result, the averaging over all initial positions results in a strong ratchet effect for solitons with small peak densities. The results obtained by direct numerical integration of the one-dimensional mean-field model show good qualitative agreement with the effective-particle approximation. Finally, we have investigated the scattering of the matter-wave solitons moving under the influence of a ratchet potential. Depending on the size of the interacting solitons, their collisions can cause either gradual or instantaneous transitions between transporting and non-transporting trajectories in the phase space. We have demonstrated that for multiple solitons of different sizes, initially formed in a harmonically trapped condensate, this effect could result in directed transport or spatial filtering of solitons.

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Formation of topological defects in Bose-condensed gases

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

1. In collaboration with the Anderson group at the University of Arizona, we have performed simulations of an evaporative cooling quench through the BEC critical point in a weak pancake-shape harmonic trap. In the experiment, it was observed that a large fraction of individual runs resulted in vortices trapped in the condensate. Calculations using the stochastic Gross-Pitaevskii equation [1] matched to the experimental growth curves also observed vortices, with statistics in excellent agreement with the experimental data. This work was published in Nature this year [2]. Ongoing work is attempting to vary the rate of condensate formation to study its effect on the density of vortices and to make a connection to the Kibble-Zurek mechanism for continuous phase transitions.

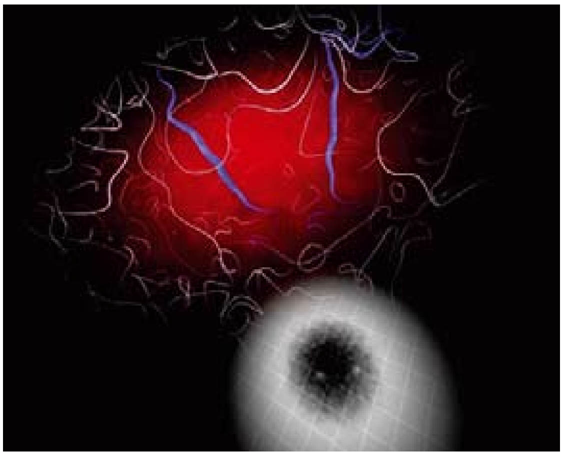

Fig. 1: Visualisation of spontaneously formed vortices in a Bose-Einstein condensate.

2. Similar quench experiments have been performed in the Engels group at Washington State University but in a cigar-shaped trapping potential. For this system geometry, it is expected that dark solitons may form along the length of the growing condensate, and this appears to be confirmed by experiment. We have been simulating evaporative cooling in this system and early results suggest that solitons form in a similar fashion to vortices in a pancake trap.

3. Quenches in multi-component Bose systems can result in the formation of domain walls. We have begun simulating the experiments of the Stamper-Kurn group at Berkeley on a magnetic field quench in an F=1 rubidium BEC that results in the preferred ground state changing from being polar to ferromagnetic. In particular, we wish to understand the effects of quantum and thermal noise in the initial state.

4. Finally, recent experiments by in the Wieman group at JILA Colorado have evaporatively cooled a ^{85}Rb-^{87}Rb system to quantum degeneracy, and observed the formation of bubbles of different condensates seperated by domain walls [5]. We have begun simulations of cooling in this system in order to understand the dynamics of the observed phase separation.

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C-field simulations of thermal Bose-Einstein condensates

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

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

2. We have modelled experiments by the University of Queensland BEC group on the formation of condensates by combining a 1D laser sheet with a cigar-shaped BEC. The laser sheet can either be applied adiabatically (in which case entropy is conserved) or suddenly (following which the energy is conserved). We have calculated the expected final condensate fraction and temperature using Hartree-Fock theory, and found good agreement with the data. A joint paper is currently in preparation.

3. A recent experiment by the Engels group at Washington State University has observed evidence for a superfluid critical velocity in dragging a both attractive and repulsive obstacles through a cigar-shpaed BEC [2]. We have been modelling these experiments with both the 1D and 3D Gross-Pitaevskii equation in order to try and interpret their data.

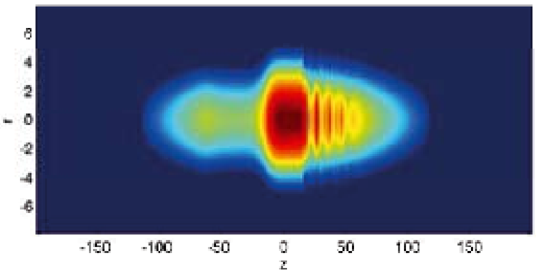

Fig.1: A laser beam passing through a cigar-shaped BEC.

4. This year saw the completion and publication of a comprehensive review paper on the development and application of c-field techniques to the dynamics and statistical mechanics of Bose gases [3].

5. Lastly, our study of the formation of vortex lattices from a rotating 2D gas was published [4].

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Grassmann Phase Space Theory in Quantum-Atom Optics

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In particle and condensed matter physics the use of anti-commuting Grassmann variables in treating fermion systems via path integral methods is a well-established approach [1]. Quantum-atom optics deals with systems such as atoms, quantised electromagnetic fields, and ultra-cold atomic gases - both fermionic and bosonic. Phase space methods (where the quantum density operator is represented by a quasi-distribution function of variables that replace the annihilation and creation operators), constitute one of the major approaches [2]. However, in spite of the seminal work by Cahill and Glauber [3] and a few applications [4, 5, 6], the use of phase space methods in quantum-atom optics to treat fermionic systems by representing (anti-commuting) fermionic annihilation and creation operators by Grassmann variables [3] is rather rare. This is particularly the case for multi-atom bosonic and fermionic systems, where many quantum modes are often involved. Generalisations of phase space distribution functions of phase space variables for a few modes to phase space distribution functionals of field functions (which represent the field operators, c-number fields for bosons, Grassmann fields for fermions) are now being developed for large systems [7].

To illustrate the applicability of the Grassmann variable approach to quantum-atom optics, it is shown that one of the most fundamental models in quantum optics and quantum physics can be treated via a Grassmann distribution function approach. The Jaynes-Cummings model of a two-level atom (TLA) in a single mode cavity involves the interaction of two simple quantum systems - one fermionic (the TLA), the other bosonic (the cavity mode). Phase space methods using a distribution function involving c-number variables (for the cavity mode) and Grassmann variables (for the two level atom) have been used to treat this model [8]. The Grassmann distribution function is equivalent to six c-number functions of the bosonic variables. Bosonic phase space integrals involving these functions determine the experimental quantities. A Fokker-Planck equation involving both left and right Grassmann differentiation has been obtained for the Grassmann distribution function. Equivalent coupled equations for the six c-number functions have been found. This feature that the final equations only involve c-numbers will also apply to more complex fermion systems.

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Phase-space Representation for Qubits

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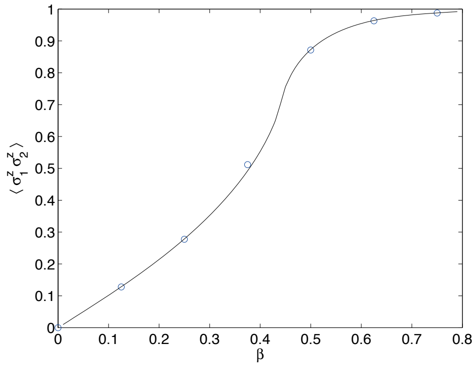
Problems involving interacting spins or qubits are often regarded as computationally intractable. These are frequently considered as only being accessible using quantum computers, which are not yet developed. At the same time, there is a 'chicken and egg' problem: it is difficult to design a quantum computer with no effective means to simulate its behaviour, including inevitable sources of loss and decoherence. In an effort to provide an avenue towards computational means to treat such problems, we have introduced a phase-space representation for qubits and spin models.

The technique uses an SU(n) coherent-state basis and can equally be used for either static or dynamical simulations. We review previously known definitions and operator identities, and show how these can be used to define an off-diagonal, positive phase-space representation analogous to the positive-P function. As an illustration of the phase-space method, we use the example of the Ising model, which has exact solutions for the finite-temperature canonical ensemble in two dimensions. We show how a canonical ensemble for an Ising model of arbitrary structure can be efficiently simulated using SU(2) or atomic coherent states. The technique utilizes a transformation from a canonical (imaginary-time) weighted simulation to an equivalent unweighted real-time simulation.



In the paper [1], the results are compared to the exactly soluble two-dimensional case. This is an important comparison, since this is the only known exactly soluble problem involving interacting spins in higher dimensions. The comparison graph shows how the phase-space simulation method compares with an exact solution, in calculating spin correlation functions. We see that there is excellent agreement even at the critical temperature. This provides evidence that the new technique gives correct results, in a case involving strong correlations and fluctuations near a phase transition.

We note that Ising models in one, two, or three dimensions are potentially achievable experimentally as a lattice gas of ultracold atoms in optical lattices. The technique is not restricted to canonical ensembles or to Ising-like couplings. It is also able to be used for real-time evolution and for systems whose time evolution follows a master equation describing decoherence and coupling to external reservoirs. The case of SU(n) phase space is used to describe n-level systems. In general, the requirement that time evolution be stochastic corresponds to a restriction to Hamiltonians and master equations that are quadratic in the group generators or generalized spin operators.

In future, we hope to develop this technique further, with a view towards treating useful problems in quantum information theory.

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Measuring the $2\,^3S_1$ lifetime of metastable helium

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Helium - the simplest multi-electron atom - is a favoured testbed for QED predictions of atomic structure. Knowledge of the He $2\,^3S_1$ state (He*) lifetime is important not just to verify QED, but also because of the key role that He* plays in many environments. In addition to being the longest-lived (metastable) state, the $2\,^3S_1$ level is the most energetic first excited state of any atomic species - some 20 eV above the ground state. Consequently He* is an important source of stored energy in ionospheric and discharge plasmas, where its large scattering cross-sections also play an important role. Furthermore, the large stored energy not only allows efficient detection of He* atoms using charged particle techniques, but the long lifetime means that the $2\,^3S_1$ level acts as an effective ground state for laser cooling via the efficient 1083nm transition to the $2\,^3P_2$ level. This makes He* a useful species for atom optics experiments where detection of individual particles is important.

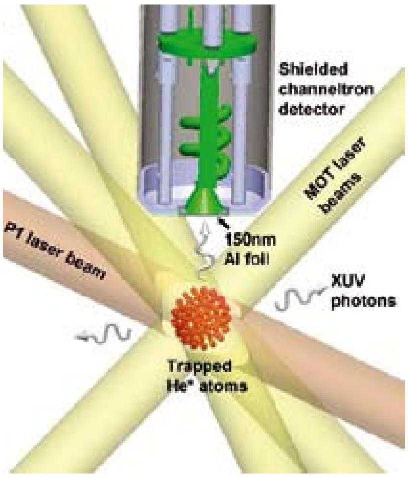

Fig. 1: Experimental schematic. The geometry of the 1083nm trapping and excitation laser beams is shown relative to the detection system, comprising the channeltron with aluminium filters and shield (quadrupole magnetic field coils not shown).

The extremely long metastable lifetime arises from the fact that direct photon decay of the $2\,^3S_1$ state to the $1\,^1S_0$ ground state is doubly forbidden by quantum mechanical selection rules. First, the metastable state shares the same angular momentum quantum number (S, l=0) as the ground state, which forbids decay via a single-photon electric dipole transition. Second, the two electrons in the metastable state have parallel spins, while the ground state is a spin anti-parallel configuration, requiring a low probability spin flip for the decay process. As a consequence, the most rapid decay process from the metastable to the ground state is via a magnetic-dipole-allowed, single-photon transition at 62.6 nm in the extreme ultraviolet (XUV), which can be readily detected.

We have determined experimentally the lifetime of the longest-lived atomic valence state yet measured - the first excited ($2\,^3S_1$) state of helium. We laser cool and magnetically trap a cloud of metastable helium atoms and measure the decay rate to the ground state via extreme ultraviolet photon emission. Two 100 nm thick aluminium filters block all ions, electrons and He* atoms from our detector while allowing the XUV photons to pass. This ensures we only count events related to a $2\,^3S_1$ atomic decay (see Fig. 1). This is the first measurement using an unperturbed ensemble of isolated helium atoms and yields a value of 7920(510) seconds, in excellent agreement with quantum electrodynamic theory [1, 2].

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** High impact article

ACQAO Success as a Centre of Excellence

The most important asset for our research is creative people. The Centre was created by a distinguished group of individual researchers who have used the opportunities given by stable long term funding to create new outstanding results. ACQAO has provided reduced teaching loads, improved laboratories and offices and the opportunity to meet other excellent researchers within the Centre and throughout the world. ACQAO has been able to provide PhD training of the highest calibre and has supported many outstanding young scientists who are now contributing to the research field in many countries.

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. The quality of the research achieved in a CoE is far higher than typically can be achieved through multiple groups of independent research grants.

Advancements and promotions of staff

During 2008 several staff members gained promotions and recognition in their universities. John Close was promoted to Professor at the ANU, Brenton Hall has been appointed to a Senior Lecturer position at SUT, Joel Corney has been appointed to a long-term position at UQ and Matt Davis was promoted to Associate Professor at UQ. This demonstrates the support given by the host Universities towards our research.

Within ACQAO the research group led by Peter Drummond and Margaret Reid has now made the successful transition from UQ to SUT, from one partner University to another.

Several individual researchers received a series of awards in 2008:

- Peter Drummond was awarded the Boas Medal of the AIP,
- Ken Baldwin received the AOS medal of the Australian Optical Society and was elected as Fellow of the American Institute of Physics for his contributions to international science,
- Nick Robins was selected as an outstanding young scientist in Fresh Science in Australia,
- Sean Hodgeman received the prize for the best poster presentation at the AIP 2008 Congress,
- Ping Koy Lam was honoured with an ANU media award,
- Murray Olsen was selected by the American Physical Society as an outstanding referee by the American Physical Society, and
- Hans-A. Bachor was elected as Fellow of the Optical Society of America for his contributions to quantum optics in Australia.

Hans-A. Bachor presenting Ken Baldwin with the AOS medal in Sydney, July 2008

In addition, Alain Aspect was awarded an Honorary Doctorate degree by the Australian National University in recognition of his pioneering work in quantum physics and the collaborations and support of ACQAO.

The collaborations between the different nodes are a crucial feature of a successful Centre of Excellence. ACQAO has fostered a series of new collaborations, both through theory groups and experimental teams that share joint equipments. Expertise is flowing freely from one project to another. We have now published several papers with joint authorship across the Centre (5 in 2008) and have ambitious proposals for new research projects that are only possible through good collaborations between the nodes and with our international partners.

UQ and ANU staff and students with Prof. W. Ertmer on the Great Ocean road trip to the AIP Congress

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, for the formation of Centres of Excellence. In particular, the Institut Francilien de Recherche sur les atomes froids (IFRAF) in France and the German Excellence Centre for Quantum Engineering and Space-Time Research (QUEST) in Germany have followed our example. We have established intensive research links and student networks with these two Centres in Europe.

Throughout the year, 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 where two cotutelle (joint PhD projects) continue, Julian Dugue and Jean-Francois Morizur, supervised by M. Leduc and C. Fabre (LKB) with J. Close and H-A. Bachor. At the same time, E. Giacobino (LKB) developed with P. Drummond, M. Reid and Q. He a novel theory of dynamical quantum memories.

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

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

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

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

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

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

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

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

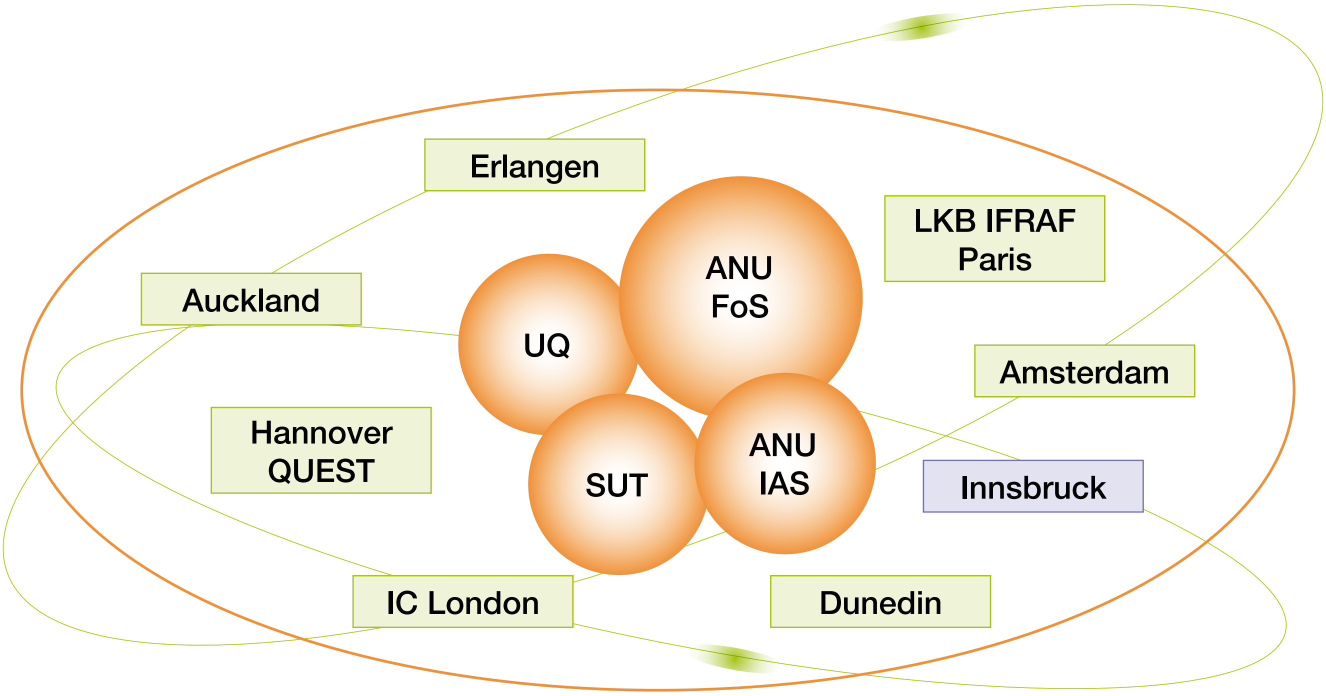
In September 2008, ACQAO was a partner with IFRAF (Paris) and QUEST (Hannover) in a two-week international symposium for young researchers on 'Quantum Manipulation of Photons and Atoms' held in Beijing and Shanghai. We sent 6 delegates to this meeting and presented and discussed the latest results of our work.

In November 2008, ACQAO organised an international workshop on 'Quantum-Atom Optics beyond Bells' in Lorne, Victoria. This brought together the quantum and atom optics community across Australia and New Zealand. This workshop had 97 delegates, including 11 international visitors, and provided a comprehensive cross-section of the activities in our field of research. This was followed by the National Congress of the Australian Institute of Physics in Adelaide where ACQAO was a Gold sponsor, including supporting further sessions and a plenary speaker.

In February 2009, we continue to participate in an international student workshop, Les Houches, France — concluding a series of six workshops for young researchers, which we organise jointly with IFRAF and QUEST. Of these, two were held in Germany, France and Australia respectively. This is a unique network that provides our young scientists access to the European research community and showcases our work in Australia as well as attracting young researchers to Australia.

Laboratories

As well as its people the other big asset in our research is our well-developed laboratories. We have excellent research facilities at the ANU and SUT that are maintained at world-class standards. In 2008, we gained support from the Major Equipment grant committee of the ANU, received LIEF funding to be shared between ANU, SUT and UQ which allowed us to create instrumentation for single atom detection. 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.



Official links and exchanges between the Centre and the international partners

ACQAO staff and students with international and national delegates in Lorne, November 2008

Commercialisation

While our research projects focus entirely on strategic fundamental goals, which are published in the open literature, we are using every opportunity to create additional intellectual property (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 2008 the Centre worked closely with many interested parties to formulate plans for future research opportunities beyond the present funding cycle. In May, the CIs took the opportunity to hear from the National advisory board members about the ideas and expectations of our external stakeholders with regard to future applications for our fundamental research. Extending the solid foundations of our quality research was clearly identified as a future direction and the best contribution we can make for several more years.

We identified several applications in metrology, remote sensing, precision instrumentation, physical standards, data communication networks, and data memories as the areas that are most likely to benefit from our research.

During the Lorne scientific workshop ACQAO continued discussions with our research colleagues from outside the Centre, from across Australia and overseas, on the future direction of our research field. We are now in the process of developing a coherent plan for the future that will build on existing research outcomes and will combine the best ideas and people in Australia.

Key Performance Measures (KPMs)

We are proud of the excellent performance within our Centre that is clearly reflected 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.

For the second phase of our Centre, 2008–2010, our negotiations with the ARC resulted in an increase in some of our KPMs to reflect the high performance of our well established Centre. We have increased the targets for some of the fundamental KPMs, in particular the number of publications, high impact publications and completion of postgraduate degrees by a factor of 1.5.

Even with this increase in 2008, we were able to not only meet all our targets but to exceed them in more than half of the categories by a factor of two or more. Several new KPMs were added, in particular in regard to international collaboration and in all these categories we exceeded our targets. These results are summarised in the table on page 53 which show the KPMs for 2008, both the outcomes and the targets with their increase, as well as the ratio between them. Performance higher than two times the target is highlighted in dark green.

Our Centre focuses on fundamental research with the aim to publish our results in the public domain, to publish ahead of others, to publish in internationally recognised journals and to make the highest possible impact in our research field. Our Centre has a thriving theory core that produces results at an ever increasing rate with a continual growth in the number of citations received. In all our experimental projects, we have not only achieved all the initial goals, which we had set ourselves, but in several cases have also completed the second generation of experiments. The details are fully covered in our science pages [pages 10–43].

Together, we were able to produce results that have appeared in 2008 in the most prestigious journals, such as Science, Nature and Nature Physics. We have both a very high rate of publication (2.3 times above our new target) and in high impact journals (2.2 times above our new target).

Our Centre has not only produced outstanding results in 2008 but is also consistent in its achievements, in many cases remaining well above target performance over its six years of operation. To document this we present the long term achievement ratio, (last column in the table on page 53), which is the average of the achievement ratios for all years since 2003. This shows that we consistently exceed our targets and initial expectations.

One most important example is the impact of our publications. The number of citations of many of our ACQAO publications has continued to grow so much that we now have a most impressive list of high impact publications. Since the inception of ACQAO in 2003 this is now at 2.9 above the target. Here we count both papers in high impact journals (impact factor>5) and those that actually have a high impact with more than 5 citations per year or 25 citations total.

We are particularly proud of the international impact and 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 (14), the fact that more than half of our 2008 publications (37) include international research collaborations, the large number of invitations (31) to ACQAO staff and students to present our research at conferences, visits to laboratories overseas (92) and the constant stream of international scientists and students who visit our Centre (23). Our staff contributes actively to many national and international committees (12), and we maintain a large number of active projects with international partners (14) that all lead to publications, as shown on pages 44–47.

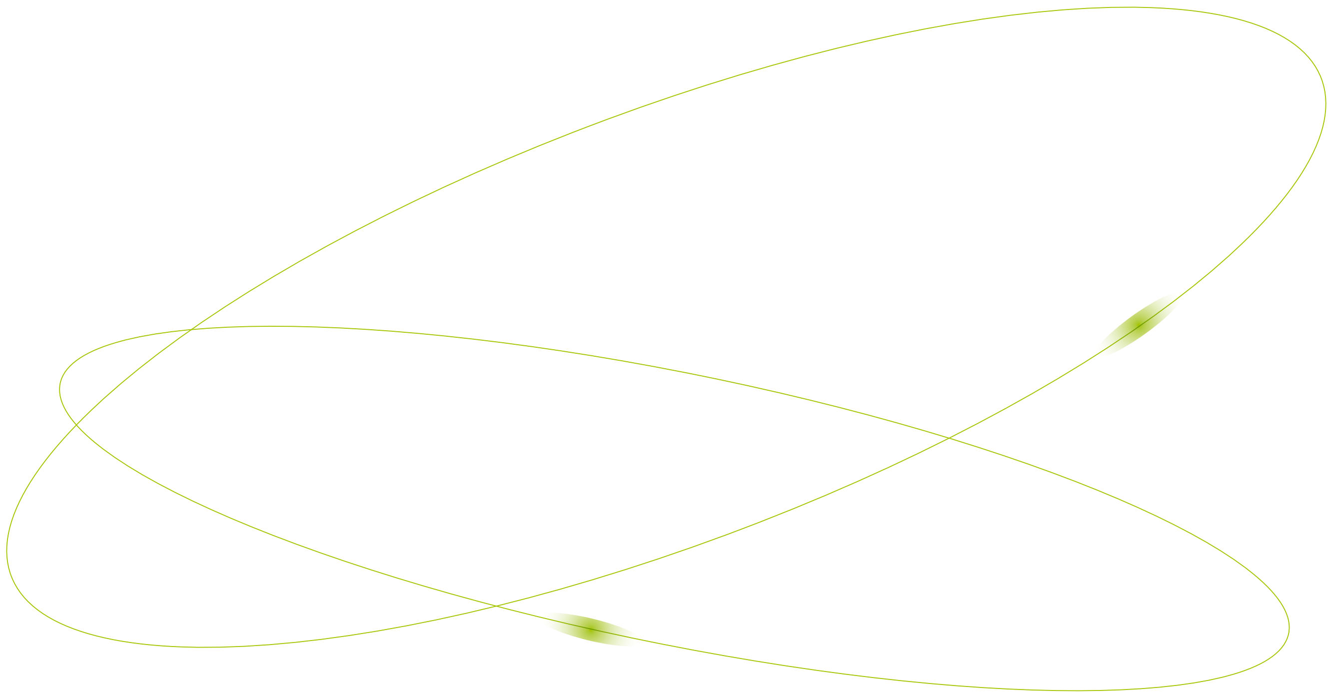
Research training and professional education is one of our major strengths, with a good number of postgraduate students (6) completing their degree while many have been recruited in 2008 (12). Many professional courses (10) and undergraduate courses (15) have been taught by our staff at all three host universities. In addition we delivered a wide range of public awareness programs to the wider public (15), which are described in more detail on page 55–56.

Key Result Areas and Performance Measures

Key Result Area	Performance Measure	Targets		2008 Outcomes	Achievement ratio	Achievement ratio 2003–08
		2008	Target increase		2008	
Research findings and competitiveness	Quality of publications	**6**	1.5	**13**	**2.2**	2.9
	Number of publications	**30**	1.5	**69**	**2.3**	2.1
	Number of patents	**0.3**	1	**0**	**0.0**	1.7
	Invitations to address and participate in international conferences	**5**	1.3	**31**	**6.2**	4.6
	Invitations to visit leading international laboratories	**8**	**NEW**	**42**	**5.3**	5.3
	Number of commentaries about the Centre's achievements	**3**	1	**14**	**4.7**	1.6
	Additional competitive grant income (# applications submitted)	**8**	**NEW**	**16**	**2.0**	2.0
Research training and professional education	Number of postgraduates recruited/year	**5**	1	**12**	**2.4**	1.9
	Number of postgraduate completions/year	**6**	1.5	**6**	**1.0**	1.1
	Number of Honours students/year	**5**	1	**7**	**1.4**	1.3
	Number of professional courses	**2**	1	**10**	**5.0**	3.3
	Participation in professional courses	**3**	1.5	**9**	**3.0**	1.2
	Number and level of undergraduate and high school courses in the Priority area(s)	**7**	1	**15**	**2.1**	2.4
International, national and regional links and networks	**Number of papers published with international co-authors/reports for internatioinal bodies**	**7**	**NEW**	**37**	**5.3**	5.3
	Number of international visitors	**15**	1.5	**23**	**1.5**	2.4
	Number of national workshops/year	**1**	1	**2**	**2.0**	1.5
	Number of international workshops/year	**1**	1	**2**	**2.0**	1.7
	Number of visits to overseas laboratories	**25**	1.4	**92**	**3.7**	3.5
	Number of memberships of national and international professional committees	**2**	**NEW**	**12**	**6.0**	6.0
	Research projects with international partners	**4**	**NEW**	**14**	**3.5**	3.5
	Examples of relevant Social Science and Humanities research supported by the Centre	**1**	1	**1**	**1.0**	1.0
End-user links	Number of commercialisation activities	**2**	1	**2**	**1.0**	0.5
	Number of government, industry and business briefings	**2**	1	**5**	**2.5**	1.6
	Number of Centre associates trained/ing in technology transfer and commercialisation	**1**	**NEW**	**1**	**1.0**	1.0
	Number of Public Awareness programs	**4**	1	**15**	**3.8**	2.3
Organisational support	**Number of new Organisations recruited to or involved in the Centre**	**1**	**NEW**	**1**	**1.0**	1.0

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

The research projects within ACQAO continue to be ambitious, supporting our long term goal of moving closer towards new quantum technologies. We monitor our achievements and compare the outcomes with the KPMs each year. Based on our excellent performance measured in this way, we are confident that we have made the best use of the resources provided and that ACQAO will continue to create research of the highest quality both now and into the future.



Outreach and media achievements

Both ACQAO staff and students share a sense of enthusiasm for their work that is evident in the various activities and awards received over the years. In 2008, this was no exception as the Centre continues to build momentum we also continued to increase our outreach activities. There is a real sense of wanting to 'spread the word' about the Centres work.

One of the most significant events for ACQAO in 2008 was to have Prof. Alain Aspect (advisory board member) receive a Honorary doctorate from The Australian National University. This celebration was marked with Prof. Aspect giving a public address, as well as being interviewed by local and national radio with live presentations. Furthermore, several newspapers including the Canberra Times ran stories relating to Alain's achievement. These events provided great opportunity to promote ACQAOs achievements and highlighted our successful international collaborations.

ACQAO is very pleased to have such an internationally recognised scientist on the Advisory Board, and congratulates Alain on his recent achievement.

Prof. Alain Aspect, Honourary Doctorate from ANU

Media recognition for our work has been significant, with more than 40 articles being reported in local and national media. A small selection is shown on page 57. The most unusual award, given to Prof. Ping Koy Lam, was an ANU Media award for his appearance in Men's Style magazine for an article on 'Men of influence under 45'.

Prof. Ian Chubb presents Prof. Ping Koy Lam with his media award (photo courtesy of Darren Boyd, ANU College of Asia and the Pacific)

The team in UQ appeared in over 27 different news websites throughout the year. In collaboration with the University of Arizona, [p. 39], the UQ team gained extensive media coverage, including a write up in ScienceDaily (www.sciencedaily.com).

The Quantum Imaging group led by Prof. Hans-A. Bachor found their results on spatial entanglement [p. 11] being reported globally. This included write ups in various popular science magazines and webpages such as Globo.com (www.globo.com), the largest news organisation in Brazil. Results for this work also received a write up in Physik in unserer Zeit (November 2008).

The demonstration of the pumped atom laser [p. 12], by Prof. J. Close and Dr N. Robins, created a similar interest including articles in popular science journals and radio interviews including September edition of Laser Focus World (www.laserfocusworld.com).

This year ACQAO participated in various trade exhibits, taking the chance to 'sell' our science in the public eye. From ICO/ACOLS, Sydney to the AIP Congress, Adelaide, where ACQAO was also a Gold sponsor of the event. Prof. Alain Aspect appeared as plenary speaker along with one of our European partners Prof. W. Ertmer. The trade booths were a great success and demonstrated our enthusiasm to communicate our science results in new and different ways.

Prof. Hans-A. Bachor and Damien Hughes as exhibitors — ICO/ACOLS, Sydney June

Prof. Hans-A. Bachor, along with several of our ANU PhD students, continued to contribute to the National Youth Science Forum (www.nysf.edu.au), which provides an excellent opportunity to spread the word amongst 290 College students from across Australia, on Physics and Science as a career for the future.

In August, ACQAO coordinated a joint outreach with several other ARC Centres of Excellence at the ANU, participating in the Canberra Careers Market. We used this opportunity to highlight to high school and college students the depth of research that is supported in Australia. Our effort to promote the career potential for young scientists in Australia was well received by students and teachers, with over 7,500 participants given the opportunity to view our work.

ACQAO was proud to support UQ students in their local workshop, KOALA, in November 2008. This proved to be a great success and highlighted the great young talent that Australia enjoys in our research field.

ACQAOs work towards quantum technologies appeared in the Swinburne University of Technology quarterly national magazine (distributed in The Australian Newpaper). Further details can be found at www.swinburne.edu.au/magazine.

Science News

Quantum Mechanical 'Hurricanes' Form Spontaneously In Super-Cold Gas

ScienceDaily (Oct. 16, 2008) — University of Arizona scientists experimenting with some of the coldest gases in the universe have discovered that when atoms in the gas get cold enough, they can spontaneously spin up into what might be described as quantum mechanical twisters or hurricanes.

The surprising experimental results agree with independent numerical simulations produced by collaborating scientists at the University of Queensland in Australia. The Arizona and Queensland researchers are reporting the results of the research in the journal Nature (October 16, 2008).

Step closer to understanding Big Bang

LaserFocusWorld

SEPTEMBER 2008 WWW.LASERFOCUSWORLD.COM

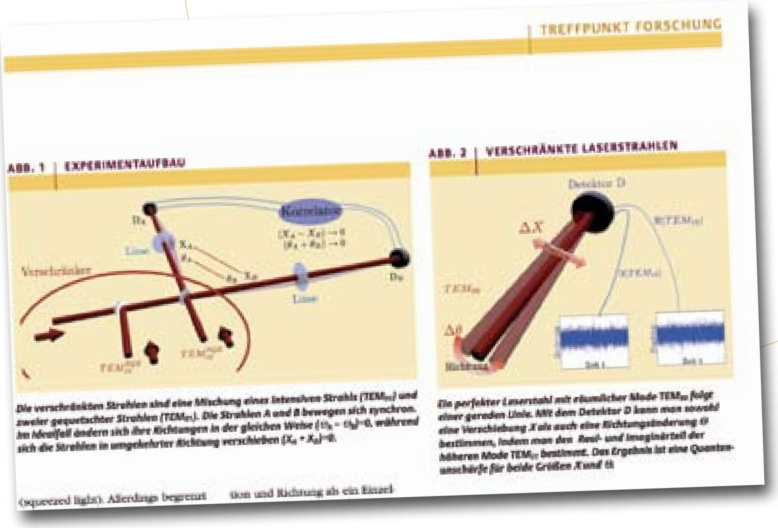
URCE FOR TECHNOLOGY AND APPLICATIONS IN THE GLOBAL PHOTONICS INDUSTRY

ATOM LASERS

Atom source for condensate is quantum leap for atom optics

Recently reported research results from Australian National University (ANU), Canberra, Australia) appear to pave the way for development of continuous-wave (CW) free-space atom lasers. Atom-optics researchers draw an analogy to the development in optics, after the first ruby laser (a pulsed device), of the first CW optical laser. To the degree that this analogy holds, the field of atom optics, including precision measuring devices such as atom interferometers (www.laserfocusworld.com/articles/292380), may be on the verge of growth analogous to the expansion in optics with the advent of laser sources.

The quantity of remaining atoms in the laser mode (red) of an atom-laser BEC (yellow) varies depending on whether or not the system is being pumped. The initial quantity (a) increases with pumping and no outcoupling (b), stays the same with pumping and outcoupling (c), and decreases with outcoupling but no pumping (d). Independence of pumping and outcoupling mechanisms



TREFFPUNKT FORSCHUNG

ABB. 1 | EXPERIMENTAUFBAU

Die verschränkten Strahlen sind eine Mischung eines intensiven Strahls (TEM$_{00}$) und zweier gequetschter Strahlen (TEM$_{01}$). Die Strahlen A und B bewegen sich synchron. Im Idealfall ändern sich ihre Richtungen in der gleichen Weise ($\theta_A - \theta_B$)=0, während sich die Strahlen in umgekehrter Richtung verschieben ($X_A + X_B$)=0.

ABB. 2 | VERSCHRÄNKTE LASERSTRAHLEN

Ein perfekter Laserstahl mit räumlicher Mode TEM$_{00}$ folgt einer geraden Linie. Mit dem Detektor D kann man sowohl eine Verschiebung X als auch eine Richtungsänderung θ bestimmen, indem man den Real- und Imaginärteil der höheren Mode TEM$_{11}$ bestimmt. Das Ergebnis ist eine Quantenunschärfe für beide Größen X und θ.

(squeezed light). Allerdings begrenzt tion und Richtung als ein Einzel-

COMPUTING

ATOM CHIP TO OPEN FRONTIERS UNKNOWN

AUSTRALIAN RESEARCHERS ARE AMONG THOSE HELPING TO PUSH THE EARLY DEVELOPMENT OF ATOM CHIPS TOWARDS NEW QUANTUM TECHNOLOGIES BY GRAEME O'NEIL

MEN OF INFLUENCE UNDER 45

PROF PING KOY LAM

40 Group leader, department of physics, ANU

FIELD OF INFLUENCE

BOLD PREDICTION

The Canberra Times Friday, D

Physicist outlines a fundamental science

By Nyssa Skilton
Medical and Technology Reporter

Quantum physics could deliver a computer capable of performing millions of calculations at a time, making it possible to decode internet security.

One of the world's leading quantum physicists, Professor Alain Aspect, will speak tomorrow at the Australian National University about the potential for technology based on the science.

He will receive an honorary degree at the ANU today.

Quantum physics is a way of understanding and describing the world at an atomic level.

Professor Aspect said it was at the root of all modern society in terms of information and communication.

computers could not compose numbers in factors, Professor Aspect said. For example, when given the number 15, a computer could not see the factors were three and five.

"The security of the commercial transactions of the internet is based on this impossibility," he said.

"If you had a quantum computer, you could split the number in factors and then there would be no more secrecy."

One way to get round this problem is quantum cryptography, which uses quantum physics to guarantee secure communication.

It allows communicating parties to create a shared string of data, which can be used as a key to encrypt and decrypt messages.

In the 1980s, Professor Aspect carried out the first experimental

Laser targets waste of space

MODERN ventures such as space travel and nanotechnology have pushed scientists to discover new ways to make increasingly accurate measurements.

If a satellite is launched at an angle that is just a minuscule amount out, the satellite could

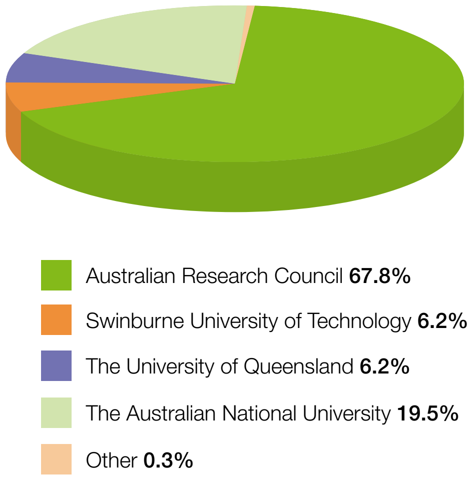
secure communication and data storage. The findings have been published in the latest edition of *Science*.

PhD student Kate Wagner, who worked on the project for two years, said it was interesting to work in a laboratory with such precision equipment.

ACQAO 2008 Annual Report Finances

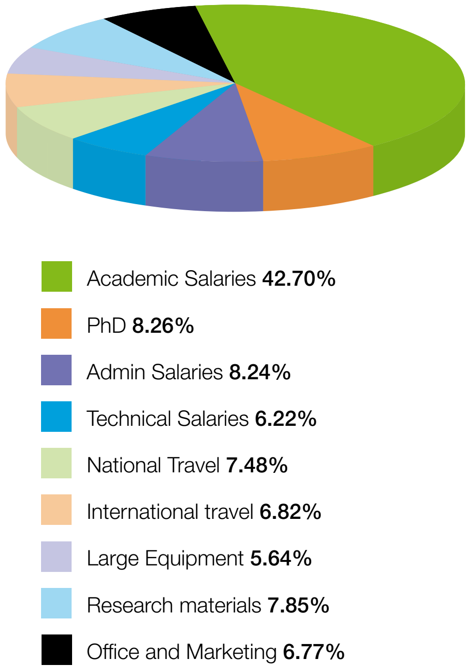
Accumulated funds	**$888,731**

ACQAO income 2008	
Australian Research Council	$2,081,309
Swinburne University of Technology	$190,000
The University of Queensland	$190,000
The Australian National University	$599,000
Other	$9,854
Total income	**$3,070,163**



ACQAO income 2008

ACQAO expenditure 2008	
Academic salaries	$1,124,559
PhD	$217,672
Admin salaries	$217,084
Technical salaries	$163,757
National travel	$197,111
International travel	$179,754
Large equipment	$148,677
Research materials	$206,882
Office and marketing	$178,307
Total expenditure	**$2,633,802**



ACQAO expenditure 2008

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

2008 Other research funding grants for ACQAO, including ARC

Donor, title, staff	Gain to ACQAO
Australian Research Council, Linkage Infrastructure, Equipment & Facilites, Quantum Limited Single Atom Detectors, Prof. J. Close, Dr N. Robins, Prof. P. Hannaford, Prof. H. Rubensztein-Dunlop	
Awarded to ANU	$125,000
Awarded to SUT	$78,125
Awarded to UQ	$46,875
ANU cash contribution	$86,000
SUT cash contribution	$100,000
UQ cash contribution	$60,000
Australian Research Council, Federation Fellowship, Prof. H-A. Bachor	$138,000
Australian Research Council, Federation Fellowship, Prof. Y. Kivshar	$132,000
Australian Research Council, Discovery Project, Quantum Simulations with Dilute Gas Bose Einstein Condensates, Dr C. Savage	$114,000
Australian Learning & Teaching Council, Competitive grant, 'Teaching Physics using virtual reality', Dr C. Savage	$110,000
Australian Research Council, Discovery Project, Detection & Control of Ultracold Atoms, Dr J. Hope	$108,000
Australian National University, Major Equipment grant, Quantum limited single atom detectors, Prof. J. Close	$100,000
Australian Research Council, Research Fellowship, Dr E. Ostrovskaya	$97,000
Defence, DSTO, Development of technology for precision atom interferometry readout and characterisation, Prof. J. Close	$80,000
Australian Research Council, Postdoctoral Fellowship, Dr Q. He	$78,000
Australian Research Council, Postdoctoral Fellowship, Dr C. Ticknor	$78,000
Australian Research Council, Postdoctoral Fellowship, Dr T. Alexander	$78,000
Australian National University, Major Equipment grant, Digital Control Experiment, Dr B. Buchler (50% ACQAO work)	$75,000
Australian Research Council, Discovery Project, Continuous Variable Quantum Information Experiments, Prof. P.K. Lam	$74,000
Australian Research Council, Queen Elizabeth II Fellowship, Prof. P.K. Lam	$74,000
National Health & Medical Research Council, Major Equipment grant, Multimode optical beams — new techniques in quantum optics and neuroscience, Prof. H-A. Bachor (50% share)	$37,000
Australian Research Council, Profossorial Fellowship, Prof. P. Drummond	$41,000
European Union, 7th Framework Prgramme, High Dimensional Entangled Systems (HIDEAS), Prof. H-A. Bachor	$27,690
Total	**$1,937,690**

2008 Personnel

ANU FAC NODE

Prof.	Hans-A.	BACHOR	Director/CI
Dr	Benjamin	BUCHLER	CI
Prof.	John	CLOSE	CI
Dr	Cristina	FIGL	Research Fellow
Mr	Neil	HINCHEY	Technical Support
Dr	Joseph	HOPE	CI
Mr	Damien	HUGHES	COO
Dr	Jiri	JANOUSEK	Research Fellow
Dr	Mattias	JOHNSSON	Research Fellow
Prof.	Ping Koy	LAM	CI
Dr	Nicholas	ROBINS	CI
Dr	Craig	SAVAGE	CI
Ms	Leanne	MICKLETHWAIT	Administration

STUDENTS

Mr	Paul	ALTIN	PhD
Mr	Seiji	ARMSTRONG	PhD
Mr	John	DEBS	PhD
Mr	Graham	DENNIS	PhD
Mr	Daniel	DÖRING	PhD
Ms	Anaïs	DREAU	Honours
Mr	Julien	DUGUE	PhD
Mr	Christian	GABRIEL	Honours
Mr	Mahdi	HOSSEINI	PhD
Mr	Michael	HUSH	PhD
Mr	Matthew	JEPPESEN	PhD
Mr	Guy	MICKLETHWAIT	PhD
Mr	Jean-Francois	MORIZUR	PhD
Ms	Rachel	POLDY	PhD
Mr	Justin	SCHULTZ	Fulbright Scholar
Mr	Ben	SPARKES	Honours
Mr	Robin	STEVENSON	Honours
Mr	Paul	SUMMERS	MSC
Mr	Michael	SZIGETI	Honours
Ms	Katherine	WAGNER	PhD

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Mr	Chris	FOSTER	PhD
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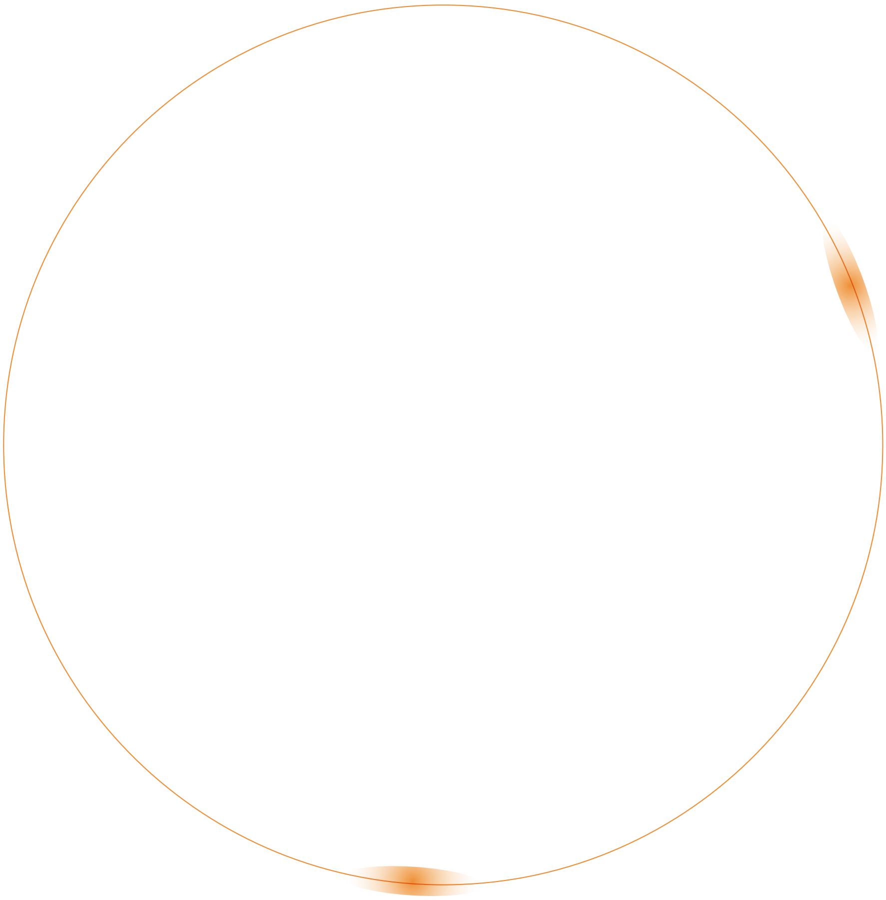
Notes



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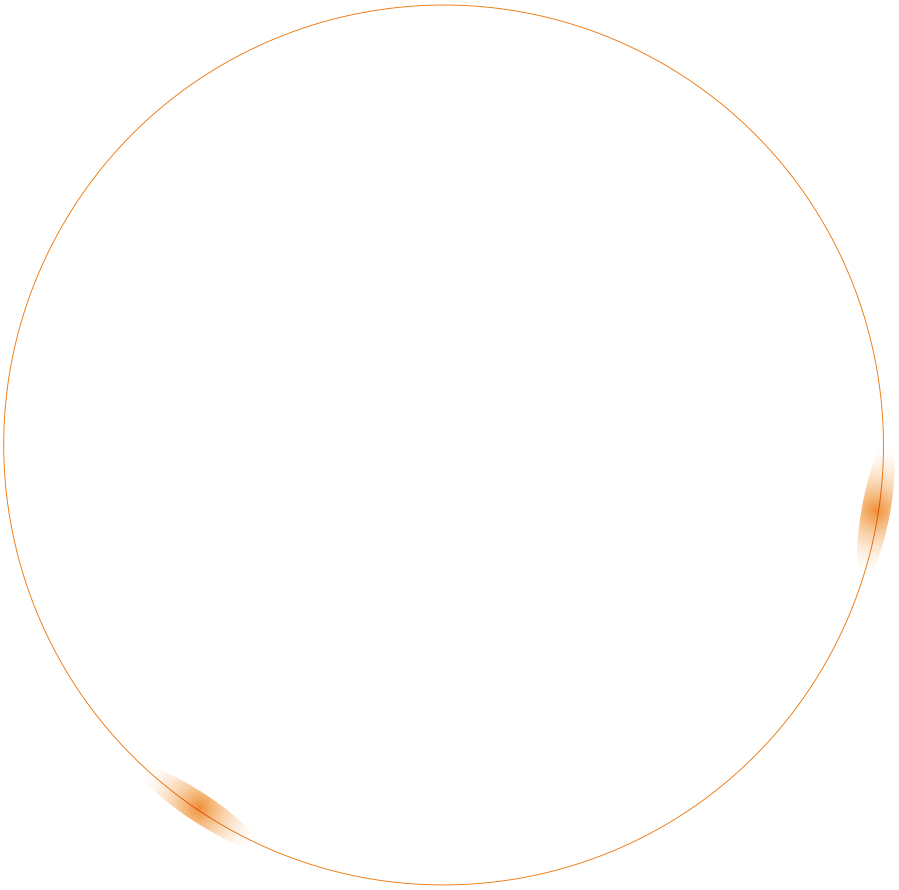

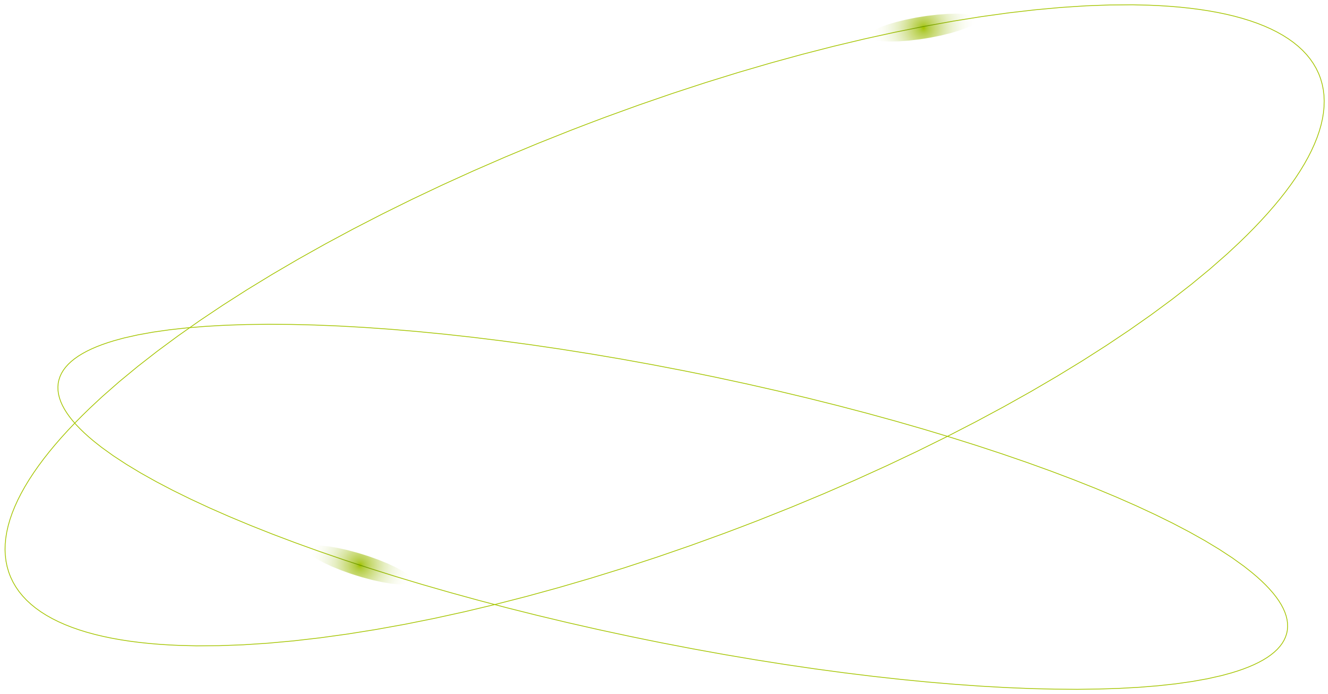

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