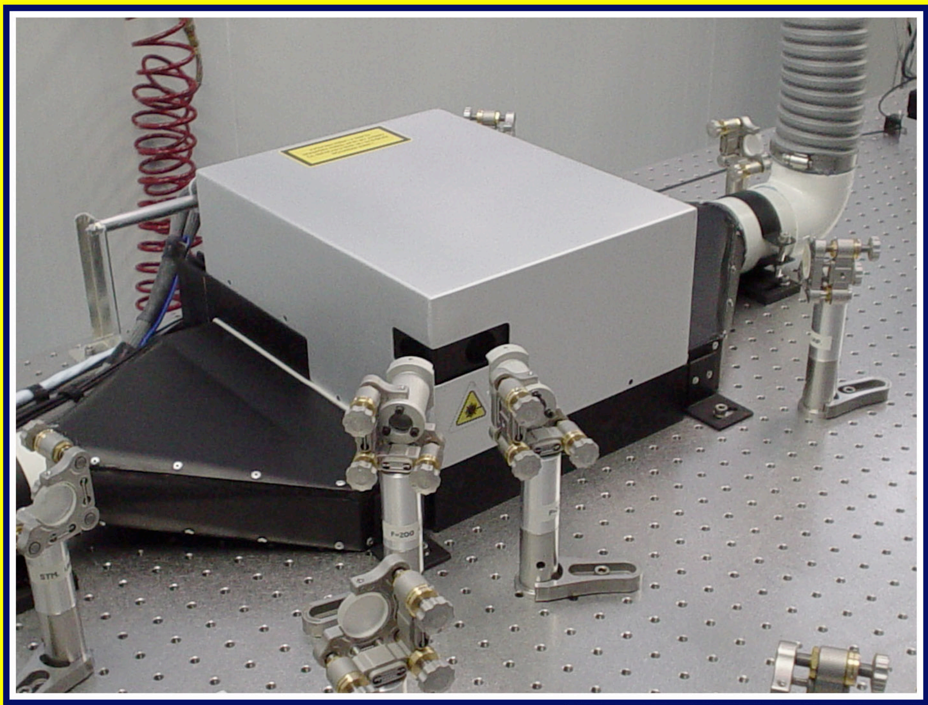
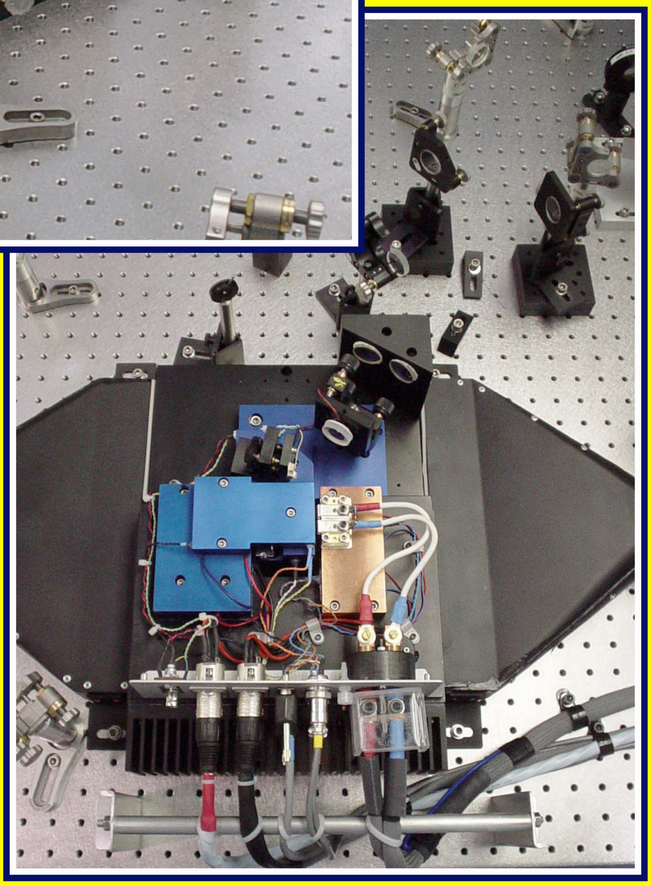
Australian Optical Society

NEWS





Volume 18 Issue 4
December 2004

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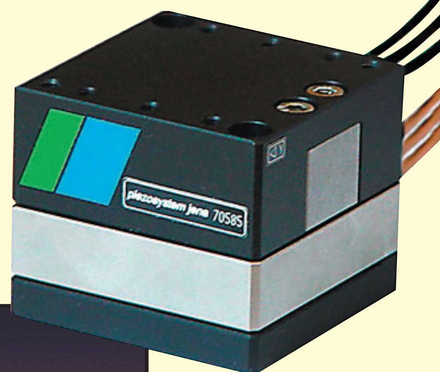

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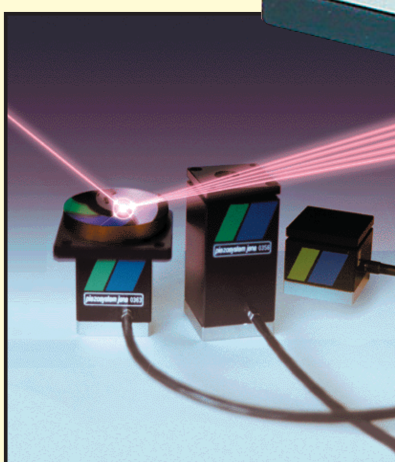

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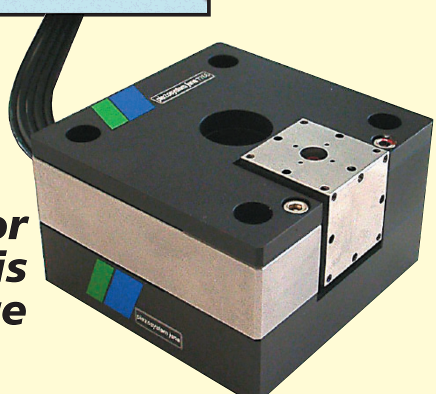

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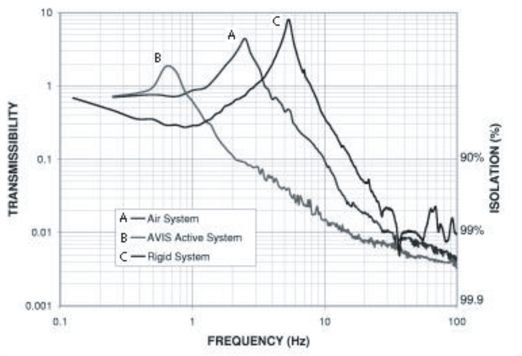

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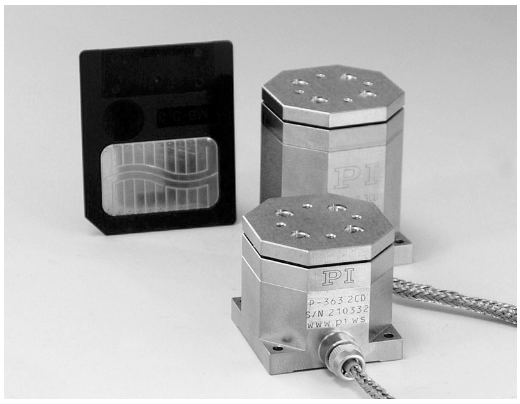

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AOS News - Editorial Board

Submission guidelines

The *AOS News* is always looking for contributions from its members. Here is a short summary of the how to make a submission.

What can you submit?

∗ ***Scientific Article***
A scientific paper in any area of optics.

∗ ***Review Article***
Simply give a run down of the work conducted at your laboratory, or some aspect of this work.

∗ ***Conference Report***
If you have been to conference recently, writing a short report would be greatly appreciated.

∗ ***News Item***
Any newsworthy stories in optics from Australia or abroad.

∗ ***Book Review***
If you have read an interesting (and relatively new) book in some field of optics please consider writing a review for the *AOS News*.

∗ ***Cartoon or drawing***
If you have some artistic bent why not consider submitting a cartoon!

How can you submit?

💻 The easiest way is by email. Either send the document text in your mail, and attach diagrams and/or a word processor file. We accept nearly all file formats. (Famous last words!).

🗐 If you don't have email access, or cannot send diagrams or pictures via email, we can accept hard copies. (One copy only is required).

Australian Optical Society website

http://aos.physics.mq.edu.au

- News
- Membership
- Optics links
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DECEMBER 2004 **VOLUME 18 NUMBER 4**

AOS NEWS

SUBMISSION OF COPY:
Contributions on any topic of interest to the Australian optics community are solicited, and should be sent to the editor, or a member of the editorial board. Use of electronic mail is strongly encouraged, although submission of hard copy together with a text file on floppy disk will be considered.

Where possible, diagrams should be contained within the document or sent as separate files. Figures on A4 paper will also be accepted. Note: all figures should be black & white or greyscale.

ADVERTISING:
Potential advertisers in *AOS News* are welcomed, and should contact the editor.

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DEADLINE FOR NEXT ISSUE
23rd February, 2005

ARTICLES

DEPARTMENTS

Cover Picture: A 10W Nd:YAG laser built at the University of Adelaide, and installed at the High Power Test Facility (for gravitational wave research) at Gingin in West Australia near Perth. An identical laser is soon to be installed at the TAMA 300 Gravitational wave experiment in Japan.

AUSTRALIAN OPTICAL SOCIETY

ABN 63 009 548 387

AOS News is the official news magazine of the Australian Optical Society. Formed in 1983, the Society is a non-profit organisation for the advancement of optics in Australia. Membership is open to all persons contributing to, or interested in, optics in the widest sense. See the back page (or the AOS website) for details on joining the Society.

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President's Report

The council has had one e-meeting since the last newsletter went out. One of the items that was discussed by the council was the very generous offer by Warsash Pty Ltd. to fund a prize for postgraduate students in the early stages of their candidature. The society is very pleased and grateful for this expression of support from one of our long-standing corporate members. The rules and scope of the prize were worked out by the council with input from Warsash, and essentially, the prize will consist of $3000 worth of equiment of the student's choice (or an equivalent discount) that is sold by Warsash, for the student who makes the best research proposal that incorporates the desired equipment. (See the anouncement on page 9.)

A second item that was discussed was the question of whether the AOS should sponsor conferences and workshops that are put on by AOS members. It was felt that the AOS is too small financially to be able to provide sponsorship as such; i.e. essentially a grant of money. It also does not have a suitable source of income for such a purpose. The society has in the past provided seed funds to conference organisers (so far mainly AOS, ACOFT, ACOLS and AIP conferences) in the form of a float or loan, with the expectation that the money is returned after the conference. This practice, which is very much in line with that of larger organisations such as the OSA, will continue. Also the AOS will happily entertain requests for endorsement of conferences run by members or groups with similar aims to the society. This can involve advertising the conference on our website among other things.

As noted in the last newsletter, the council has resolved to make changes to the AOS Newsletter, with the payment of an honorarium (of $500 per issue) to the new editor, when a new editor is appointed. A new editor is still being sought – see the advert in this issue. We are also in the process of revamping the editorial board and to try to get a better representation for the various geographical areas in Australasia where the AOS members are.

This issue marks a major change in the presentation of the AOS Newsletter. We have broken with tradition and introduced a full colour cover with advertising, in response to requests/suggestions from various corporate members who regularly advertise in the newsletter. The traditional arrangement whereby corporate members can place two pages of adverts in the body of the newletter remains.

In this issue we have articles and reports by two more of the recent prize winners. Kirk McKenzie of the ANU was one of the winners of the OSA/SPIE prizes for the best presentations by students at the ACOFT/AOS conference held in Canberra in July. Kirk has written this presentation up for the AOS news and it is in this issue. These awards have now been formalised in the Memoranda of Understanding between the AOS and each of the OSA and SPIE.

In addition Joseph Hughes, also of the ANU, won the AOS Postgraduate student prize last year. This prize helps to fund travel to an overseas conference, and Joseph has written up a report on the conference that he attended, for this issue.

The next AOS conference will be part of the upcoming 16th National Congress of the Australian Institute of Physics, at the end of January 2005, and I would urge all of you to get behind this meeting and give it your full support. I look forward to seeing you all there!

On the subject of conferences, I would like to congratulate John Love and Chris Walsh have been successful with the bid that they repared for the International Commission for Optics (ICO) conference in 2008 to be held in Australia.

Murray Hamilton
President, Australian Optical Society
November 2004

A word from the Honorary Treasurer

The only way the AOS can continue to service the needs of the optical community within Australia including conferences, regular newsletters, scholarships, prizes and a political voice, is through the regular payment of subscriptions. Unfortunately each year some members fail to renew – in some years up to 20% of our membership have not continued their membership. Fortunately overall membership numbers have remained roughly constant in recent years through the inclusion of new members.

The subscription paid by each full AOS membership is a ticket to discounted membership fees for SPIE (US$20), the Optical Society of America (US$15) and the Australian Institute of Physics (10%); these discounts add to more than the $43 annual subscription. Timely payment of your AOS membership will ensure that you can claim these discounts for 2005! Student members of the AOS are eligible to apply for certain prizes.

Recently an email was sent to remind members to renew for 2005. If you are uncertain of your current financial status please read the message in small print on your AOS News mailing label. This message is a way to remind members of their membership status.

How to renew:

- Complete the form in the back of AOS News;
- Or, look up http://aos.physics.mq.edu.au and then click on *Joining* in the left side navigation bar.

Thank you

Stephen Collins
Honorary Treasurer, Australian Optical Society

Position Vacant

Australian Optical Society Newsletter

Editor

The AOS is seeking an editor for the newsletter. This is a quarterly publication conveying optics news, scientific articles and optics advertising to the Australian Optics community.

The editor will be paid an honorarium of $2000 p.a or $500 per issue.

Applications for this position should be addressed to the President of the Society, Dr Murray Hamilton

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The 13th International Congress on Photosynthesis

Joe Hughes,
Laser and Optical Spectroscopy Group, Research School of Chemistry, Australian National University

The 13th International Congress of Photosynthesis was held in the unique city of Montreal, Canada August 29th to September 3rd. Montreal is one of those cities able to captivate and entertain its guests, without any overzealous effort or desire to do so. Montreal and the province of Quebec provide a unique pocket of French culture and heritage transcribed to North America. This was indeed a fitting host for an era where the leaders in photosynthesis research are fruitfully combining traditionally distinct research disciplines.

The congress attracted over 900 delegates from internationally renowned institutions, traversing disciplines spanning plant physiology, molecular biology, spectroscopy, and theoretical/computational chemistry. Fundamental aspects of photosynthesis research received their usual quota of attention, however a noticeably very broad range of research areas was covered. This incorporated a symposia session on Emerging Techniques, including Single Molecule Spectroscopy applied to biological protein complexes.

Australian photosynthesis research was very well represented at the congress with ten speakers, nine of which came from the Australian National University including a plenary lecture by Susanne von Caemmerer of the Molecular Plant Physiology Group at ANU. I presented recent results from the Laser and Optical Spectroscopy Group at the Research School of Chemistry at ANU in the symposia session "Type II Reaction centres: Excited State Dynamics and Donor Side". The talk provided evidence showing that the paradigms embedded in 20 years of Photosystem II research need revising. In particular, the primary electron donor in Photosystem II, P680, does not abide by its much-used analogy to the better-understood bacterial reaction centre primary donor. P680 is the photo-active entity in Photosystem II and has an oxidising potential high enough to oxidise water to molecular oxygen, thus providing all the O_2 on the planet. We received a high level of interest and positive feedback on these results, and the "Type II Reaction centres: Excited State Dynamics and Donor Side" discussion session revolved predominantly around the results and issues raised in my presentation.

A theme of photosynthesis conferences in recent years is the report of new X-ray crystal structures for Photosystem II, and the 13th international Congress of Photosynthesis was no exception. Jan Kern (Max Volmer Laboratories for Biophysical Chemistry, Berlin, Germany) presented recent results at 3.2-Å resolution from the supplying more detailed information of the protein environment of various significant co-factors. He provided a very balanced view of recent structural studies, and offered cautionary advice in over-interpretation of the Photosystem II crystal structures, given the current levels of resolution. The mechanism of water oxidation by the catalytic manganese cluster, and consequently its structural details are an extremely valued prize in Photosystem II research. Such caution regarding over-interpretation of structural data was therefore a very refreshing acknowledgement.

A highlight of the conference social calendar was the 2nd George Cheniae Blues Concert and Smoked Meat Night. Bill Rutherford, who has been involved in Photosystem II research for many years, and his famous Baskerville Blues Band put on a stellar performance, enticing many delegates to the dance floor to show that science is not the only thing at which they excel. Equally at ease whether behind the podium or on stage, Bill left his "scientist cap" at home, and played the part of the quintessential blues showman, donning dark sunglasses, guitar and harmonica. He bellowed his songs with all the enthusiasm he could muster. This was surely a night not to be forgotten, and hopefully its place has been cemented among future photosynthesis congresses.

(Joe Hughes was the recipient of the AOS Postgraduate Student Prize in 2003, which partly supported his attendance at this conference. Ed)

Awards for AOS members in 2004

AOS Medal 2004: Ross McPhedran, University of Sydney

OSA/SPIE Student prizes 2004: Paul Steinvurzel, University of Sydney and Kirk McKenzie, ANU

Australian Government Eureka Prize for Promoting Understanding of Science 2004: Ken Baldwin, ANU
"From bogongs to scientists - a new Canberra tradition, as science experiments with Parliament"

Australian Computer Society Eureka Prize for ICT Innovation, 2004: Optical Fibre Technology Centre
"From butterfly wings to optical fibres and the instant internet"

2004 Victoria Prize: Keith Nugent, University of Melbourne
"for pioneering work with quantitative phase imaging"

WARSASH/AOS STUDENT PRIZE – ANNOUNCEMENT

Warsash Pty Ltd has very generously offered to fund a prize for postgraduate students who are in the AOS. The council of the AOS together with Warsash has instituted the following rules for this prize.

1) Title: WARSASH/AOS STUDENT PRIZE

2) A prize comprising up to $3000 worth of equipment, or a $3000 discount on the sale price of equipment whose retail price exceeds $3000, will be provided annually by Warsash Scientific Pty Ltd. for the best student research proposal meeting the criteria laid out below. The equipment will chosen by the winner from that equipment which is normally offered for sale by Warsash.

3) Eligibility: Students enrolled in a postgraduate degree by research in an Australasian university are eligible to apply for this prize. The student must be a member of the AOS and be in the first or second year of their candidature.

4) Application: The student must submit a research proposal (maximum 6 pages of 12pt font, including his/her CV) that sets out the aims, methodology, and significance of the proposed research. A brief description of how the Warsash equipment fits into the research plan must be part of the proposal. Two letters of support from an academic referees must accompany the application. One of these must be from the student's supervisor and must include confirmation that the equipment supplied by Warsash will be used appropriately in the proposed experiment.

5) Judging: The applications will be judged on the basis of scientific merit by a panel of three AOS members, convened by the President or Vice-President.

6) The judging will be based on three factors:
the general excellence of the candidate, as indicated by the CV and the letters of reference
and whether the research proposal is thorough, exciting
and clearly explains the impact of the research and the reason why the particular piece(s) of equipment is(are) essential.

7) Ownership of equipment that is awarded in this prize will lie with the university in which the student is enrolled.

8) Due date for applications: Applications will close on the 30th of June each year.

AOS MEDAL

The Australian Optical Society is seeking nominations for the next award of this medal, which is for an outstanding contribution or contributions to the field of optics in Australia by a member of the Australian Optical Society.

This Medal is the most prestigious award of the Australian Optical Society. It would normally be presented only to a nominee at an advanced stage of his or her professional career and with a strong and sustained record of authority, enterprise and innovation in the field of optics in Australia.

Nominations for the next AOS Medal should include brief personal details and a curriculum vitae emphasising the main contributions made by the nominee to Australian optics. Two letters of recommendation should also be provided. Nominations may be made either by or on behalf of any eligible candidate. The selection panel reserves the option to seek additional information about candidates for the award.

The closing date for nominations is 15 February.
Nominations should be sent to the Secretary

Atom chips and Bose-Einstein condensates

Chris Vale
School of Physical Sciences, University of Queensland, Brisbane 4072, Qld, Australia.

Abstract
Ultra-cold atoms and Bose-Einstein condensates (BECs) provide a dramatic example of a quantum system on a macroscopic scale. Atoms can be cooled down to temperatures below 1μK and their de Broglie wavelengths become large enough to be readily observed in experiments. This has spawned a new research area known as atom optics which refers to the study and control of atoms based on their wave nature. In recent years, physicists have been performing experiments with coherent atoms from a Bose-Einstein condensate. The ability to produce and manipulate condensates above microfabricated surfaces may one day lead to new technologies such as atom interferometers on a chip.

1. Introduction

Physicists have long known that some of nature's most interesting phenomena can be seen at extremely cold temperatures. The quest to cool atoms down to temperatures approaching absolute zero has lead to several remarkable achievements. Laser cooling techniques, developed in late eighties and early nineties, were able to produce clouds of atoms at temperatures colder than had been seen anywhere in the universe! At first glance laser cooling may seem a counter intuitive prospect (lasers are often used to drill or machine materials through localised intense heating) however, it is also possible to cool with laser light. This relies on the absorption of laser photons at one frequency, and the emission of photons at a (slightly) higher frequency, so that the atoms give up some of their kinetic energy to an emitted photon. With many absorption and emission cycles, this process can result in remarkably effective cooling and microKelvin atom temperatures are routine. At such low temperatures, the de Broglie wavelength of the atoms, $\lambda_{dB} = h / \sqrt{2\pi m k_B T}$, grows to the point where it can readily be seen in experiments. The atoms behave very differently from classical Newtonian particles and are instead described by the laws of quantum mechanics.

In the mid nineties a further breakthrough came when researchers at JILA, MIT and Texas were able to cool atoms down even further, to sub-microKelvin temperatures, creating a Bose-Einstein condensate (BEC). This required an additional cooling technique, evaporative cooling, which allowed them to achieve lower temperatures and higher densities than could be reached with laser cooling alone. A Bose-Einstein condensate is a truly macroscopic quantum system which consists of typically between 10^4 to 10^6 atoms all in the same quantum state. Also, as these atoms must be amenable to laser cooling, they have strong optical transitions. These allow us to image them with resonant laser light obtaining very good signal to noise ratios.

Bose-Einstein condensates have now become a valuable tool for probing many aspects of atomic and many-body quantum physics. Recently, condensates have been produced in miniature magnetic traps formed by current carrying wires patterned onto a substrate [1,2]. Such devices are known as "atom chips" and are finding wide application in efforts to coherently control matter for new atom optical devices [3,4]. One promising application is an atom interferometer [5] based on coherently splitting and recombining atom clouds and measuring interference of the matter waves. In this article, I will begin by describing the operation of such a chip-based interferometer. I will then present a brief review of Bose-Einstein condensation and how it was realised at the University of Queensland using an atom chip. This provides an ideal starting point for experiments based on the coherent control of matter and may one day lead to chip-based BEC technologies.

2. Magnetic microtraps and the two-wire atom interferometer

The combination of two parallel current carrying wires and a uniform magnetic field creates a versatile scheme for manipulating cold atoms. A schematic of this arrangement is shown in Fig. 1.

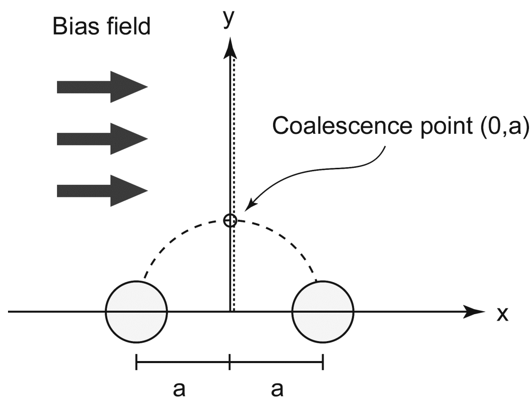

Figure 1: Two parallel wires separated by a distance 2a carry current out of the page. A homogeneous magnetic field is applied in the x-direction which cancels the field of the wires at certain points on the dotted and dashed lines, depending on their relative strengths. This provides a range of possibilities for trapping atoms in two dimensions.

When an atom with a magnetic dipole moment, $\boldsymbol{\mu}$, is placed in a magnetic field, $\boldsymbol{B}$, it experiences an interaction potential $U = -\boldsymbol{\mu}.\boldsymbol{B}$. If the projection of the magnetic moment onto the field remains constant during the atom's motion, the adiabatic condition is satisfied (ie. the atom remains in the same magnetic substate, m_F). In such cases the potential is given by the scalar expression, $U = -m_F g_F \mu_B B$ where g_F is the Landé g-factor, μ_B is the Bohr magneton and $B = |\boldsymbol{B}|$. Atoms whose magnetic moments align antiparallel to $\boldsymbol{B}$ are known as weak-field seekers as they can lower their energy by occupying regions of low field. Such atoms can therefore be trapped in a minimum of the magnetic field.

The two-wire and bias field scheme of Fig. 1 can act as a two dimensional trap or waveguide for weak-field seeking atoms. There are three regimes in which it can operate and these are displayed in the magnetic potential contour plots of Fig. 2.

In the weak bias field regime, $\beta < 1$, there are two traps, separated vertically from each other. The upper trap is not as tightly confining as the lower one as can be seen by the spacing of the contour lines. Around each minimum, the field has quadrupole symmetry with a linear field gradient. At the critical bias field, $\beta = 1$, the two quadrupole traps coalesce into a single hexapole trap. Further increasing the bias field, $\beta > 1$, splits this again into two symmetric quadrupole traps separated horizontally. The dotted and dashed lines on Fig. 1 show the path of the minima as the bias field is varied.

This scheme offers the possibility of realising a highly sensitive atom interferometer [5]. The operation of the interferometer

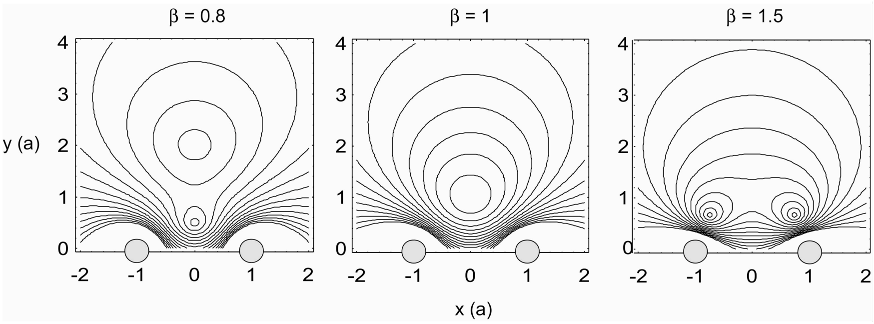

Figure 2: Contours of the magnetic potential for three different values of the normalised bias field, β. As the bias field is increased, two vertically separated traps move together and eventually coalesce into a single trap. Further increasing the bias field splits this into two symmetric horizontally separated traps.

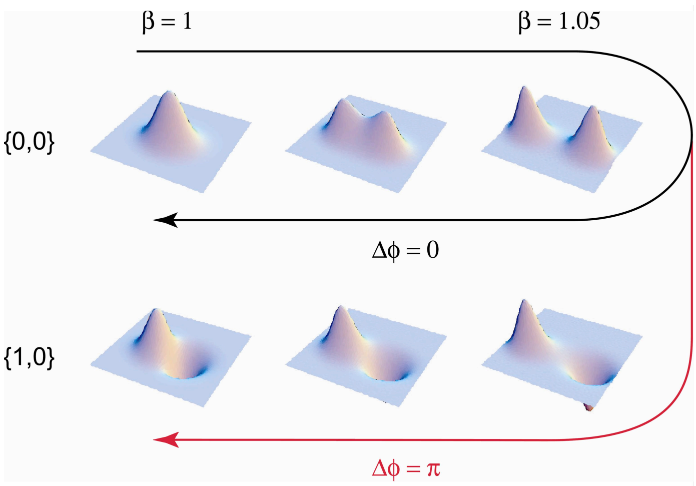

Figure 3: Plots of the ground {0,0} and first excited {1,0} state atomic wavefunctions of the two wire waveguide. As the bias field is increased adiabatically, the ground state wavefunction splits into two symmetric components. After being held apart for some time the components may acquire a relative phase, $\Delta\phi$, in the presence of an asymmetric perturbation. When the bias field is reduced back to the coalescence value $\beta = 1$, the phase difference shows up via the relative populations of ground and first excited states.

begins by loading a Bose-Einstein condensate into the ground state of the coalesced waveguide, ($\beta = 1$). Next the bias field is ramped up so that the potential and condensate wavefunction split symmetrically into two components. The speed of the splitting should be carefully controlled to avoid exciting unwanted modes and destroying the coherence of the two components. Once separated, the two components are left to evolve at their respective positions. Any asymmetric perturbation to the system which causes a relative shift in the energies, $\Delta E = E_L - E_R$, of the two components results in a phase difference, $\Delta\phi$, between the two components of the wavefunction given by $\Delta E\tau / \hbar$, where τ is the measurement time. The phase shift is measured when the bias field is reduced back to the critical value. A phase shift of zero yields the initial wavefunction, while a phase shift of π adiabatically evolves into the first excited vibrational mode of the guide at $\beta = 1$. Phases in between are given by the relative populations in the ground and first vibrational excited states. Figure 3 shows this process schematically. Calculated ground and first excited state atomic wavefunctions (found by numerically solving the 2D time dependent Schrödinger equation) are plotted as the bias field is varied adiabatically. At high bias fields the two states approach degeneracy and only a very small asymmetric perturbation is needed to (nonadiabatically) couple the two states.

Readout of the interferometer is possible via careful measurement of the populations in the ground and first excited states. Schemes to spatially separate the ground and first excited state populations, based on the slight anisotropy of the guide, have been formulated but not yet tested experimentally. Calculations show that such interferometers will be extremely sensitive for measurements of magnetic and electric field gradients and gravity.

3. Bose-Einstein condensation

At the remarkably low temperatures which can be achieved by laser and evaporative cooling, individual de Broglie waves of atom in a gas become very large and the interactions between atoms is no longer classical. Instead, the atomic de Broglie waves scatter off and interfere with each other and a quantum description of the processes is necessary. An important factor in determining the behaviour of these quantum gases is whether the particles possess integer or half integer spin. Particles with integer spin are known as Bosons and those with half integer spin are known as Fermions and the physics of these two kinds of particles is markedly different.

In order to understand Bose-Einstein condensation, we start with the Bose-Einstein distribution function (Eq. 1) which was first calculated by Bose and Einstein in the 1920s,

$$\langle n_i \rangle = \frac{1}{e^{(\varepsilon_i - \mu)/k_B T} - 1} \tag{1}$$

This equation tells us the mean number of Bosonic particles, $\langle n_i \rangle$ we expect to find in an eigenstate with energy ε_i of a quantum system. It depends on the chemical potential μ and the thermal energy of the system, given by Boltzmann's constant multiplied by the temperature, $k_B T$. The chemical potential, μ, is the amount of energy required to add or remove a particle from the system. It depends on the temperature and number of particles in the system and accounts for the fact that the total number of particles must be conserved. As the temperature is lowered the chemical potential grows (becomes less negative), eventually approaching its limiting value, equal to the ground state energy, ε_0. For $\mu > \varepsilon_0$ the denominator in equation 1 would become negative and the distribution nonphysical.

If we insert this limit of ε_0 in to equation 1, we are left with an expression which tells us the upper limit on the allowed occupation of all of the excited states, ($\varepsilon_{i \neq 0}$), but no longer contains any information about the total number of particles, as μ no longer appears in the expression. That is, the system may contain any number of particles at a given temperature, but the number which occupy the excited states is restricted. Any remaining or additional particles must therefore lie in the ground state of the system, ε_0, where it can be seen that the distribution blows up. This collection of particles in the ground state is the Bose-Einstein condensate and may become truly macroscopic. In experiments, up to 10^7 atoms have been prepared in the ground state and the total population in all of the excited states can be around one hundred times smaller.

The atoms in a condensate are all described by the same wavefunction making them an ideal source for coherent atom interferometry. Experiments aimed at realising the interferometer described in the previous section using atoms from a BEC are currently underway in several laboratories around the world.

4. Bose-Einstein condensation at UQ

At the University of Queensland, we have produced a Bose-Einstein condensate of rubidium atoms on an atom chip [6]. Our atom chip was fabricated entirely in-house using only materials and machinery readily available to typical laboratories. A 125µm silver foil was glued onto a 1mm thick machinable ceramic substrate using ultra high vacuum (UHV) compatible epoxy. Silver was chosen as the conductive material as it has the lowest resistivity of all metals (1.59µΩcm) and is highly reflective (97%) to light resonant with the Rb D2 transition at 780nm required for laser cooling. The silver foil was polished to a mirror finish and then wires were cut into the chip using a micromechanical cutter and a computer controlled milling machine. A picture of the finished chip is given in figure 4.

This figure shows the electrical connections and rubidium dispenser. Also visible are the wires patterned onto the chip. These consist of two parallel Z-trap wires with a centre to centre separation of $2a = 0.4$mm, and two additional endcap wires for varying the axial confinement. The parallel Z-wires are capable of producing fields suitable for realising the two wire guide described above.

We have used our atom chip to produce Bose-Einstein condensates of ^{87}Rb atoms. The experiment follows the usual stages for BEC production and details of our procedure are given below.

First, rubidium vapour is injected into the vacuum chamber from a pulsed dispenser source. We collect approximately 10^8 atoms in a reflection magneto-optical trap (MOT) formed 4.5mm from the surface of the chip. Following the dispenser pulse, atoms are held in the MOT for a further 10s to allow the vacuum to recover. After this time, the atoms undergo a compression phase (by changing the frequency of the lasers and field gradients in the MOT) before being optically pumped into the $F = 2$, $m_F = 2$ ground state and loaded into the magnetic trap. The magnetic trap is formed by turning on a current of 4A through both Z-wires on the chip and a transverse magnetic field of 12G produced by external coils. The transverse field is then ramped up linearly to around 30G over 500ms to produce a tighter trap closer to the surface in which efficient evaporative cooling can take place.

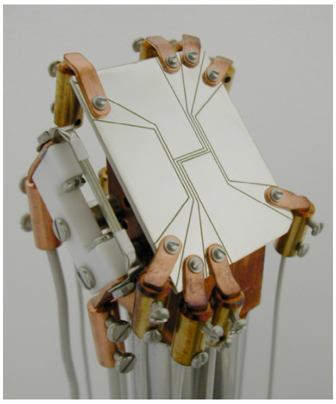

Figure 4: Photograph of the atom chip before being placed in the vacuum chamber. The electrical connections via copper tabs are visible on the four corners of the chip. The rubidium dispenser can be seen on the left side of the chip mount.

The atomic cloud is evaporatively cooled through the BEC transition using a single logarithmic sweep of an applied radio frequency (RF) magnetic field from 13MHz to around 1MHz in 10.5s. Figure 5 shows absorption images of atom clouds following 15ms of free expansion after being released from the magnetic trap. This trap formed 200µm from the chip surface with oscillation frequencies of 1100Hz radially and 6Hz axially. The three images show clouds after terminating the RF evaporation at 1080kHz, 1050kHz and 1010kHz, respectively. On the left is a 700nK thermal cloud, in the middle a partially condensed cloud (BEC surrounded by thermal cloud) at 450nK and on the right an almost pure BEC below 250nK. The condensate contains around 5×10^4 atoms and has a peak density of 4×10^{14} cm^{-3}. With our parameters the critical temperature for condensation is around 500nK which is crossed with approximately 1.2×10^5 atoms.

5. Fragmentation

When cold atom clouds are brought close to wires carrying current, the atomic distribution is seen to break up into "fragments" [7-9]. This is due to microscopic deviations in the direction of current flow which produce small components of magnetic field parallel or antiparallel to the axis of the wire [7]. This effect may prove to be a limitation of current carrying wire based atom chips for applications such as atom interferometry.

We also observe fragmentation of cold clouds brought close to the chip surface. Figure 6 shows an absorption image and an averaged cross-sectional profile of a 4µK fragmented atom cloud that was prepared at a distance of 45 ± 5µm from the surface of our chip.

Fragmentation appears to be highly dependent on the geometric and material properties of the conductors [10]. Our method of chip fabrication may be beneficial in this regard, as the solid metal foil should have superior conductor uniformity to electroplated wires. It remains to be seen how precisely wires can be patterned into a solid foil, and subsequently, how this affects fragmentation which we will investigate in future work.

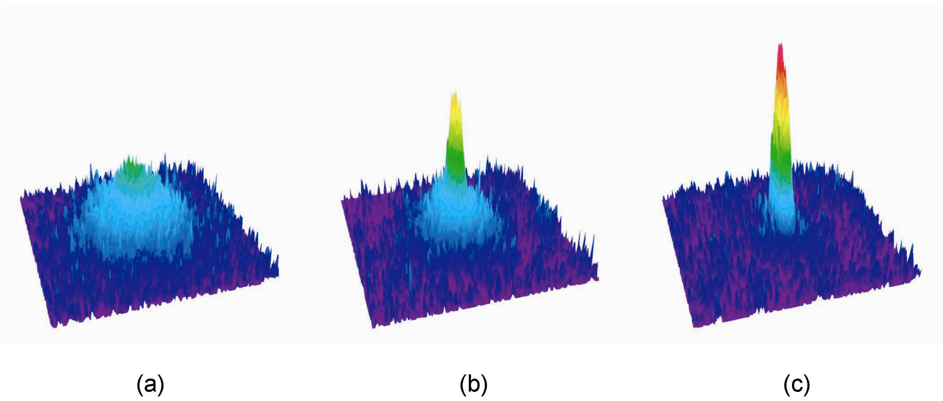

Figure 5: False colour images showing the absorption of (a) a thermal cloud at 700nK, (b) a partially condensed cloud at 450nK and (c) an almost pure BEC after 15ms free expansion. A condensate is seen to form below the critical temperature of 500nK.

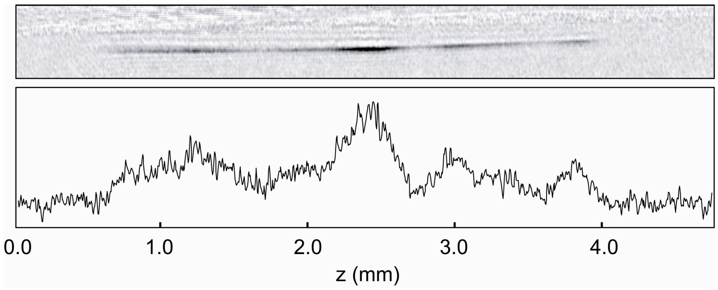

Figure 6: Absorption image and cross-sectional profile of a 4μK fragmented atom cloud prepared at a distance of 45μm from the chip surface.

Regardless of this, our higher current carrying capacity allows us to produce moderately tight traps further away from the conductors which is important as fragmentation is seen to scale approximately as $e^{-ky}/\sqrt{ky}$, where k is the wavenumber of the (spatial) current deviations [9]. This will allow us to perform experiments at distances further from the surface than other groups where fragmentation effects become negligible.

Fragmentation is one of the technical hurdles that researchers are currently working to overcome in order produce new technologies based on the coherent control of BECs on chips. Electron beam lithography has been shown to be a more precise way to prepare straight conductors and we plan to use these in the future to access even tighter trapping potentials close to the chip surface.

6. Conclusion

The intention of this article is to provide an overview of some of the interesting developments in the field of Bose-Einstein condensates on Atom Chips. The overriding theme of this work is the control and manipulation of (atomic) quantum systems. Efforts towards building chip-based interferometers are ongoing in several laboratories around the world including those of Nobel laureates Wolfgang Ketterle at MIT and Eric Cornell at Boulder Colorado. Australia is also an important contributor in this field with two working BEC experiments (ANU and UQ), another well on the way at Swinburne University and the recently established Australian Centre of Excellence for Quantum Atom Optics. At UQ we intend to use our BEC for studies of interferometry in double well potentials, dynamics in modulated traps and we are developing techniques for detecting single atoms from condensates which will allow us to study atom number statistics of BECs.

Acknowledgements

Our work is supported by the Australian Research Council.

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When quantum noise is deafening

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Abstract:
Giant laser interferometers for detecting gravitational waves are now coming on line. These first generation detectors will be limited by quantum noise above 200 Hz. Future upgrades will be quantum noise limited over most of the acoustic gravitational wave detection band. Overcoming the quantum noise limit is therefore an active and exciting area of research. We discuss some recent discoveries and report the production of low frequency quiet light - squeezed light - which is a key to enabling quantum limits to be beaten.

Introduction:
Gravitational waves (GW's), or ripples in the curvature of space-time, are predicted in Einstein's General Theory of Relativity. Their existence has been confirmed by observing the energy loss of the 'binary pulsar' due to gravitational wave emission. Hulse and Taylor won a Nobel Prize in 1993 for this work. Today, the direct detection of gravitational radiation remains a major goal of fundamental physics. Observation of gravitational waves will allow rigorous examination of the General Theory, previously untested in the nonlinear, strong gravity limit. The effort to detect gravitational waves is therefore one of the frontier physics projects. Direct detection will allow a new way of sensing the universe – akin to using our sense of hearing for the first time. Information obtained will be complementary to electromagnetic observations, revealing processes that occur in the core of cataclysmic astrophysical events and at the earliest moments of the Big Bang. New events will be recorded igniting a revolution in astronomy comparable with the advent of radio astronomy.

The most promising technology for gravitational wave detection is long baseline (km scale) laser interferometry. A passing gravitational wave will alternately stretch then contract one arm of a Michelson interferometer whilst contracting then stretching the other arm, changing the interference condition. Being in the audio frequency range and causing matter to move, GWs have been likened to 'sounds' coming from the universe. The problem of detection is that the effect is extremely small: expressed as a relative length change, ! L/L, it is of the order of 10^{-22}

A major international effort over the last 20 years has led to a global array of interferometric detectors, LIGO[1], VIRGO[2], GEO[3] and TAMA[4], nearing their design sensitivities. These detectors are based around the Michelson interferometer and employ long arm lengths (up to 4km) in ultra-high vacuum and use advanced techniques to reach the design sensitivity. Noise sources such as seismic vibrations, acoustic vibrations, thermal noise (arising from the Brownian induced motion of the mirror surface) and laser intensity and phase noise have to be isolated or suppressed to unprecedented levels. Once these classical sources of noise have been made negligible, the quantum fluctuations of the electromagnetic field remain to potentially mask the 'sounds of the universe'. The question is: what can one do when quantum noise is deafening?

In this paper, we briefly review quantum noise and how it limits an interferometer and discuss a number of novel solutions for reducing or avoiding quantum noise.

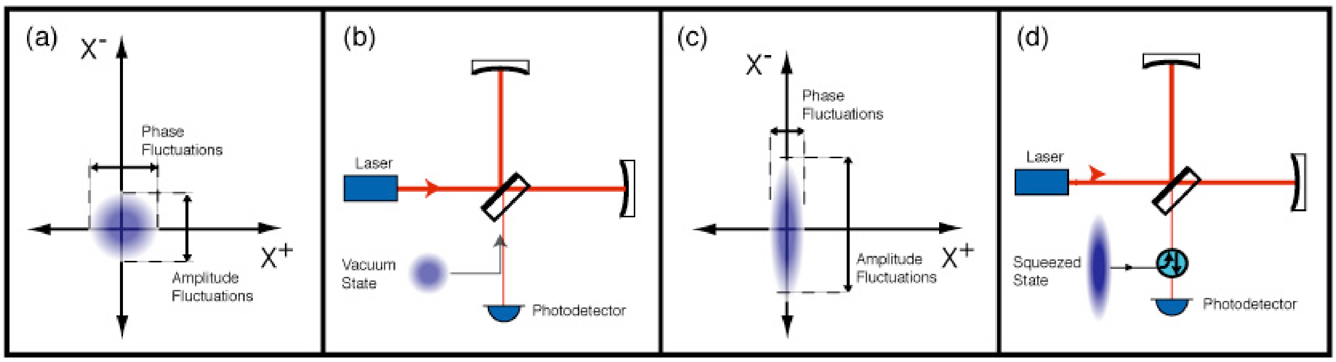

Figure 1: Representation of (a) a vacuum state, (b) a Michelson interferometer, (c) a phase squeezed state, (d) injection of a squeezed state into the unused port of a Michelson interferometer. The axis labels in (a) and (c) are amplitude quadrature 'X^+' and Phase quadrature 'X^-'.

These techniques are broadly referred to as quantum non demolition (QND) and this is an exciting and fertile field of research with many new ideas emerging over the last few years. Many of the QND techniques require a source of light know as squeezed light [5]. Until this year no such source existed in the audio frequency region, a requirement for long baseline detectors. We end our paper by presenting experimental results of a squeezed source in the audio gravitational wave detection band.

Quantum Noise in Interferometric Gravitational Wave Detectors:

Long baseline interferometers are length controlled to interfere constructively towards the input (laser) port of the Michelson interferometer and destructively towards the output (photodetector) port. Thus, unless a differential signal occurs in the arms, no light exits towards the photodetector. However, quantum mechanics dictates that there must be a minimum uncertainty 'vacuum state', shown in figure 1 (a), that enters the output port of the Michelson, as shown in figure 1 (b), and this interferes constructively towards the photodetector. The vacuum state has quantum fluctuations in the amplitude and phase quadratures and is the source of quantum noise limit in the interferometer. The vacuum fluctuations in the phase quadrature, which is the GW signal quadrature, are called shot noise. Although the vacuum amplitude quadrature fluctuations are not in the signal quadrature, they too can limit the sensitivity by coupling into the phase quadrature. The amplitude quadrature fluctuations cause the Michelson arms mirrors to move differentially, via unequal radiation pressure force and this causes a differential phase shift in the arms. The shot noise contribution is frequency independent, whereas the radiation pressure noise is largest at low frequencies, and reduces higher frequencies as 1/frequency squared. The standard quantum limit (SQL) is where the optimum sensitivity occurs and this is at the frequency where shot noise and radiation pressure noise are equal amplitude.

Beating quantum noise – Quantum non-demolition techniques

The quantum noise limit was recognised in the early years of the field, however has only been reached recently in the long baseline interferometers. The QND techniques invented to overcome the quantum noise limit are described in this section.

<u>Squeezing:</u> Squeezed states of light have noise less than the shot noise limit one quadrature at the expense of an increase in the noise in the conjugate quadrature, see figure 1 (c). In 1980, Caves realised that the sensitivity of an interferometer could be improved by using a squeezed state injected into the outport port of the Michelson, as shown in figure 1 (d) [6]. If shot noise is the limiting noise source, squeezing the phase quadrature improves the sensitivity. This allows the SQL to be reached at a lower laser power level, but not surpassed. While experiments are some way off reaching the SQL, the use of phase squeezed light to reduce shot noise has been experimentally demonstrated by Grangier et al [7] and Xiao et al [8]. Most recently, the authors demonstrated shot noise reduction in a power recycled Michelson interferometer [9]. If the interferometer is limited by radiation pressure noise, light squeezed in the amplitude quadrature is required to improve the sensitivity, again at best to the SQL.

<u>Quantum entanglement</u>: Injecting phase squeezed vacuum with a 45^{O} phase shift into the output port correlates radiation pressure noise with shot noise, and this allows a sub-SQL measurement to be made [10]. In theory, the noise reduction that can be achieved is limited only by the level of squeezing. Due to the strong frequency dependence of radiation pressure noise (arising from the suspended mirror's transfer function), this noise cancellation only occurs at one frequency unless frequency dependent control of the squeezed quadrature is implemented. A experiment that demonstrated the cancellation of (classically) correlated amplitude and phase noise was performed recently at the ANU [11].

<u>Dynamical correlations:</u> The proposed Advanced LIGO configuration is shown in figure 2 (a). It was realised by Buonanno and Chen [12] that this configuration, which has a 'signal mirror' inserted at the output port of the interferometer, can also induce correlations between the amplitude and phase quadratures similarly to quantum entanglement described above. These correlations also can result in the interferometer beating the SQL.

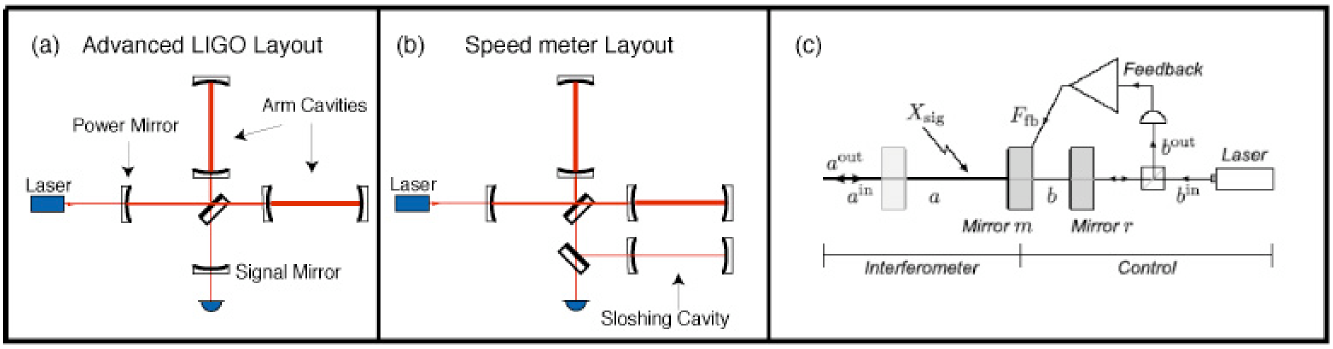

Figure 2: (a) The proposed Advanced LIGO configuration. This layout has a 'power mirror' increase the signal amplitude and a'signal mirror' to increase the lights signal interaction time. (b) A speed meter layout. Here the signal mirror has been replaced by a sloshing cavity. (c) A experimental layout for quantum locking, taken from reference [16].

Speed meters: The principle behind a speed meter configuration [13,14] is to read out the GW signal from a momentum (speed) measurement rather than a position measurement. In contrast to position, momentum is a QND variable allowing repeated measurement without disturbance. One variant of speed meter, shown in figure 2 (b), the signal mirror is replaced with a 'sloshing cavity'. Light carrying the position information sloshes back into the interferometer with a 180^o phase shift cancelling the position information in that cavity (provided the signal frequency is much less than sloshing frequency) and leaving only a phase shift proportional to the relative velocity of the test masses. A simplified speed meter configuration has been performed experimentally [15].
Quantum locking: Quantum locking [16,17] is a form of quantum control in which secondary cavities pumped with light of low power are placed behind the main arm cavities (see figure 2(c)) to control the cavity mirror in the radiation pressure noise dominated regime, without increasing shot noise which dominates at high frequencies. Detuned optical cavities operated in reflection in the local feedback loops allow optimal cancellation of back action. This is new physics involving both non-linear cavity dynamics and the resulting noise cancellation, both of which are yet to be experimentally realised.

Low frequency squeezed states
All of the QND techniques described above either rely on squeezed states to introduce the required quantum correlations or can be improved with the addition of squeezed states. For the squeezed state to be applicable to GW detectors it must be squeezed at the GW signal frequencies. For ground based detectors the GW signal detection band is 10Hz – 10kHz. Squeezed states at such low frequencies had not previously been demonstrated, since noise sources such as laser classical amplitude and phase noise are large at low frequencies and this generally limits squeezing to above ~ 1MHz [18].

Previous attempts to produce low frequency squeezed light have been based on common mode cancellation techniques to null any classical noise in the squeezed beam and 'recover' the squeezing. This technique was able to bring optical parametric amplification (OPA) squeezing from ~ MHz down to ~80kHz[19] and more recently ~50kHz[20].

Our investigation into below threshold optical parametric oscillation (OPO) revealed an inherent immunity to many previously limiting classical noise sources. This was apparent in the theory for the squeezed beam out of a below threshold OPO. The theory of the squeezing obtained an OPO and an OPA is very similar, and contains contributions of noise from; the classical laser noise in the seed beam and in the second harmonic pump beam, and from acoustic induced cavity detuning fluctuations. These sources have limited the production of squeezing to higher frequencies in the past. In theory, terms due to both pump and detuning noise are scaled by the intra-cavity coherent field at the fundamental wavelength. Thus if the system is in below threshold OPO operation, i.e. without a coherent seed beam, then the intra-cavity coherent fundamental field is zero. In this case the noise from the pump and detuning fluctuations does not couple into the squeezed beam. Also, since there is no coherent seed, only vacuum fluctuations enter the input coupler, so there is the minimum seed noise allowed by quantum mechanics. For low frequency squeezing the immunity of below threshold OPO to seed, pump and detuning noise is an important outcome we demonstrated experimentally [21].

Low Frequency Squeezing Experiment
The experimental schematic is shown in figure 3 (a). An Nd:YAG laser was used to pump the second harmonic generator (SHG) and to provide a a local oscillator beam for the homodyne detection scheme. The OPO cavity was not locked during the measurements, rather it was brought on resonance manually where it stayed for ~10 sec.

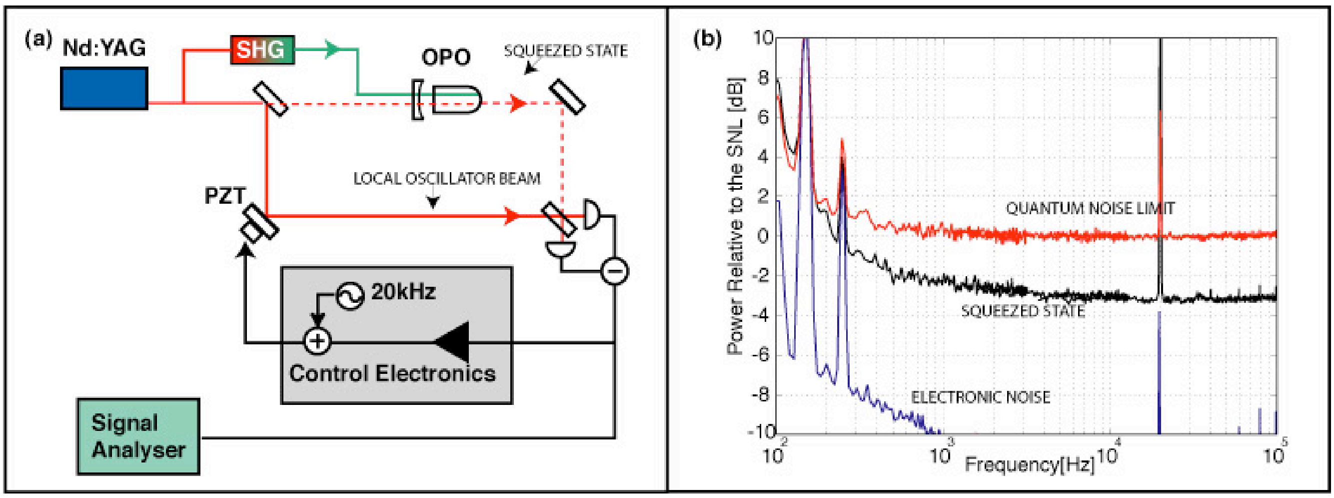

Figure 3: (a) A schematic of the OPO experiment. (b) OPO spectrum measured on the homodyne detector.

The squeezed state was measured on a homodyne detector, which consists of a 50:50 beam-splitter and two photodetectors. The local oscillator is interfered with the squeezed state on the beam-splitter. The difference of the photocurrents is proportional to the fluctuations of the squeezed state. The homodyne phase (the phase difference of the local oscillator beam and the squeezed state) was controlled so that the homodyne detector measured the squeezed quadrature. An error signal for phase difference was obtained from the noise power of the squeezed state. This error signal was generated by modulating the homodyne phase (at 20kHz), detecting the noise power at high frequency (2MHz) and demodulating. This control technique requires no coherent amplitude in the squeezed beam, unlike standard techniques, thus the squeezed vacuum state from the OPO could be locked.

Results:

The OPO spectrum from 100Hz to 100kHz is shown in figure 3 (b). The top trace is the shot noise limit of the homodyne detector, the black trace is the spectrum of the squeezing. The residual peak at 20kHz is a result of the dither frequency of the homodyne phase. The squeezing starts near 200Hz and continues up to 100kHz. This is the lowest frequency squeezing to date and, importantly, is covers most of the audio GW signal band. The amount of squeezing is 3dB over most of the band but reduces below about 1kHz. Measurements below 100Hz were unable to be recorded as the system stability was limited by the unlocked OPO. These results indicate that OPO operation offers immunity to classical noise sources.

Conclusions:

Quantum noise will be the major source of noise in future long base line gravitational wave detectors. Beating or avoiding quantum noise is currently an active and exciting field of research with many clever ideas now emerging. Many of these ideas rely on the generation of squeezed light at audio frequencies of interest to gravitational wave detection.

We have produced the lowest frequency squeezing to date with the frequency of the squeezed source corresponding to that where first generation detectors, such as LIGO, are shot noise limited. These detectors are believed to be on the verge of the sensitivity required for the first ever detection. Our squeezed source could already improve its sensitivity above 300 Hz. By 500Hz our source produces 3.6dB below the SNL (inferred). If optimally coupled into LIGO the shot noise limited strain sensitivity could be improved by a factor of 1.5, equivalent to using a laser of 2.25 the power. The sensitivity increase would correspond to increasing the volume of the universe that events can be detected by a factor of 3.5.

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Harnessing Quantum Entanglement

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(Dated: November 22, 2004)

We review recent experiments with trapped ions demonstrating the deterministic creation and manipulation of entangled states. Our discussion focusses on the demonstrations of dense coding and teleportation by the NIST group, the techniques used, and the potential application to large-scale quantum information processing.

I. INTRODUCTION

Dramatic progress in micro- and nano-fabrication of hardware for information processing has made encoding information within a single atom a practical possibility. In this limit the quantum nature of the information carriers becomes important, and it has been shown that quantum effects can provide significant improvements in efficiency for a small number of important computational problems [1, 2]. The importance of these problems has stimulated intensive efforts aimed at the development of large scale quantum information processing (QIP), and a wide range of physical systems have been considered [3, 4]. Independent of the implementation, a central requirement for QIP is the deterministic creation and manipulation of entangled states and this has now been well established in the ion-trap system [5–10, for example].

The ion-trap system achieves a high level of control of both the external and internal states of the atom making it an ideal candidate for large-scale QIP. Most importantly the ion-trap system satisfies the main requirements for a quantum computer as outlined by DiVincenzo [4, pp. 1-3]: (1) a scalable system of well-defined qubits, (2) a method to reliably initialize the quantum system, (3) long coherence times, (4) the existence of universal gates, and (5) an efficient measurement scheme. Most of these requirements have been demonstrated experimentally, and emphasis has now shifted towards issues of scalability and the demonstration of fundamental QIP protocols. Here we focus on experiments carried out at NIST but note that similar work is being pursued at Aarhus, Almaden (IBM), Hamburg, Hamilton (Ontario, McMaster Univ.), Innsbruck, Los Alamos (LANL), University of Michigan, Garching (MPI), Oxford, and Teddington (National Physical Laboratory, U.K.). We give a brief account of the latest experiments carried out at NIST and the techniques used which illustrate the key features necessary for large-scale QIP.

II. TRAPPED ION QUBITS

In the trapped-ion system atomic ions are confined in linear radio-frequency (Paul) trap [11]. When cooled the ions form a linear array along the trap axis (referred to as the z-axis) and their motion is well described by normal modes [12]. In the ^{9}Be$^+$ experiments at NIST, each qubit

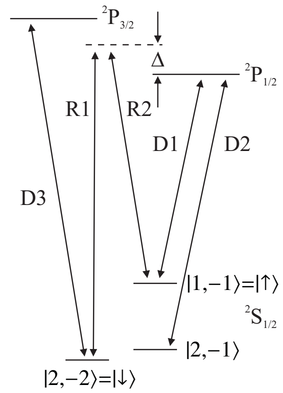

FIG. 1: Relevant energy-level structure for ^{9}Be$^+$. The ^{2}S$_{1/2}$ levels are labels by their F, m_F quantum numbers. Beams D1, D2, and D3 are all polarized σ^-. Raman beams R1 and R2 are polarized π and σ^+/σ^- respectively, with a detuning $\Delta \simeq 2\pi \times 80$ GHz. For all beams $\lambda \simeq 313$ nm

is encoded in a single ^{9}Be$^+$ ion using the two ground-state hyperfine levels $|\downarrow\rangle \equiv |F = 2, m_F = -2\rangle$ and $|\uparrow\rangle \equiv |F = 1, m_F = -1\rangle$, which are separated in energy by the hyperfine splitting $\omega_0 \simeq 2\pi \times 1.25$ GHz. These qubit states are referred to as the spin-states in analogy with a spin half system. The relevant level structure is shown in Fig. 1.

A. Initialization and detection

In a typical experiment the ions are first Doppler cooled using the the σ^- polarized D3 beam, with beams D1 and D2 providing any necessary optical pumping [13]. Sideband cooling cycles are then used to pump each motional mode to the ground-state. Each cooling cycle is achieved using beams R1 and R2 to drive stimulated Raman transitions from $|\downarrow, n\rangle$ to $|\uparrow, n-1\rangle$, followed by optical pumping to $|\downarrow, n-1\rangle$ using beams D1 and D2 [14]. A sequence of typically 20 to 30 cooling cycles is usually sufficient to cool a particular mode to the ground state. The final optical pumping step also serves to initialize each qubit to the state $|\downarrow\rangle$. Note that multiple modes can be cooled by interleaving cooling cycles for each mode.

Detection in the ion trap system is achieved by state-dependent fluorescent measurements using beam D3. In a typical detection time of 200 μs a state-detection efficiency of $\sim 99.9\%$ can be achieved [15].

B. Coherent Qubit Manipulation

In addition to sideband cooling, the Raman beams R1 and R2 provide the means to coherently manipulate the qubit states. A detailed account of these manipulations can be found in Refs. [5, 16, 17]. Here we summarize only the most relevant features. Since the Raman beams have a large detuning from any allowed transition, any excited state can be adiabatically eliminated and the interaction is that of a two-level system with an effective field, $E_{\text{eff}} = E_0 \cos(\mathbf{k} \cdot \mathbf{x} - \omega t + \phi)$. In this expression ω, ϕ and $\mathbf{k}$ are, respectively, the frequency difference, relative phase and difference k-vector of the two Raman beams and $\mathbf{x}$ denotes the position of the ion. For simplicity we restrict our discussion to a single mode of motion along the z-axis with oscillation frequency ω_z. We also assume $\mathbf{k}$ to be parallel to the z-axis so that $\mathbf{k} \cdot \mathbf{x} = kz$ where $k = |\mathbf{k}|$. With an appropriate choice of ω the effective field E_{eff} can be used to implement either single qubit rotations or a two-qubit phase-gate.

1. *Single Qubit Operations*

With $\omega = \omega_0$, the Raman beams drive "carrier" transitions $|\downarrow; n\rangle \leftrightarrow |\uparrow; n\rangle$. When k is non-zero the transition rate depends on n and the complete dynamics is highly dependent on the motional state. However when $k = 0$ or the motion is cooled to the ground-state, the evolution is given by the single qubit rotation

$$R(\theta, \phi) = \cos(\theta/2) I + i \sin(\theta/2) \cos(\phi) \sigma_x + i \sin(\theta/2) \sin(\phi) \sigma_y, \quad (1)$$

where I is the identity operator, σ_x, σ_y, and σ_z denote the Pauli spin matrices in the $\{|\uparrow\rangle, |\downarrow\rangle\}$ basis ($\langle\uparrow| \equiv (1, 0), \langle\downarrow| \equiv (0, 1)$), θ is proportional to the duration of the Raman pulse, and ϕ is the relative phase of the Raman beams as introduced above.

For each ion, one is free to choose $\phi = 0$ for the first pulse by formally using the unitary transformation $|\uparrow\rangle \rightarrow e^{i\phi}|\uparrow\rangle$, $|\downarrow\rangle \rightarrow |\downarrow\rangle$. However, all subsequent operations must be referenced to this choice. To illustrate, consider a simple two-ion experiment in which two pulses corresponding to $R(\pi/4, 0)$ are applied. Before applying the second pulse, the trapping potential is altered so that the second ion moves an amount δz such that $k\delta z = \pi$. For the first ion, the net operation is given simply by $R(\pi/4, 0)R(\pi/4, 0) = R(\pi/2, 0)$. However, for the second ion, the additional phase shift due to the ion's movement results in $R(\pi/4, \pi)R(\pi/4, 0) = I$. Thus, the net effect is a $\pi/2$-pulse on the first ion only. In this way individual qubit rotations without the need for individual laser beam addressing can be achieved [8, 9, 15, 18].

2. *Entanglement*

A fundamental requirement for quantum computing is an entangling operation and a number of such operations have been demonstrated in the ion-trap system. The CNOT gate as proposed by Cirac and Zoller [19] has been demonstrated by the Innsbruck group [6]. A CNOT and π-phase gate, between the motion and internal state for a single ion, have been realized at NIST [16, 20, 21]. Also, using the scheme suggested by Sørensen and Mølmer [22, 23] and Solano *et al.* [24], a gate between two qubits was realized [18, 25]. A gate that has proven very robust and experimentally flexible in a number of recent experiments [7–9] is the phase gate reported in [5].

When the Raman beams have a frequency difference close to a mode frequency ($\omega = \omega_z + \delta$) they no longer drive qubit transitions but impose a dipole force on the ions. Under appropriate conditions this dipole force provides a sinusoidal forcing of the ion with frequency ω and a spin-dependent force amplitude [5, 17]. Since the forcing is close to resonance it drives an excitation of the motional mode and, due to the detuning δ, the motion returns to the ground-state in a time $T = 2\pi/\delta$. During this time a phase is accumulated which depends on the force amplitude and therefore the spin-state. This is the basis of the two ion phase gate discussed in [5] which yields the transformations

$$\begin{aligned} |\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle, \quad |\uparrow\downarrow\rangle \rightarrow e^{i\Phi}|\uparrow\downarrow\rangle \\ |\downarrow\uparrow\rangle \rightarrow e^{i\Phi}|\downarrow\uparrow\rangle, \quad |\downarrow\downarrow\rangle \rightarrow |\downarrow\downarrow\rangle, \end{aligned} \quad (2)$$

where $\Phi = -\pi/2$.

It is important to note the phase gate can be applied to more than two ions. Indeed it has been successfully applied in three ion experiments [7, 9] and can potentially be applied when a different species is present, as in sympathetic cooling experiments [26]. Additionally, the phase gate is robust against small amounts of heating (provided the Lamb-Dicke limit is satisfied). Indeed, even when one of the motional modes has a thermal energy as large as $\bar{n} = 1$, the gate still has a fidelity as high as 0.9 [9]. Also the phase gate does not require individual addressing, is carried out by a single pulse, and does not require the use of an additional internal state.

C. A Multiplexed Architecture

As the number of ions in the trap increases it becomes increasingly difficult to spectrally resolve individual vibrational modes [4, pp. 69-88],[16]. Additionally it is necessary in some protocols, such as teleportation [9] or error correction, to measure and reset individual qubits. To avoid decoherence of other qubits from the associated scattered light it is therefore desirable to perform such measurements in a spatially separated trap. These and other reasons have led to the consideration of a large array of interconnected traps with each trap holding only a relatively small number of ions.

For a detailed account of the architecture proposed by the NIST group see Refs. [16, 18]. In this scheme ions are shuttled between trap nodes by applying time-varying potentials to 'control' electrodes. The basic building block of this type of architecture was reported in [11] in which ions were moved between two separate trapping zones. Separating ions proved difficult in that substantial heating was observed, the separation was not always reliable, and the time-scale for separation was much longer than anticipated (10 ms). However, improvements in trap design have significantly reduced these problems. For example, the trap used in the demonstration of teleportation [9] achieves reliable separation in $\sim 200\ \mu$s with no detectable failure rate (for 10^4 separation events) and vibrational heating as low as $\bar{n} = 1$.

Experimental demonstrations needed to establish feasibility of the proposed architecture are discussed in [27, pp. 295-306] and include:(1) the demonstration of multiple trap arrays; (2) the movement of ions between nodes; (3) reliable separation and recombination of ions; (4) sympathetic recooling; and (5) robust single-qubit and two-qubit gates. The demonstration of teleportation incorporates to some extent all but the sympathetic recooling. Although recooling was not needed for the teleportation experiment due to the low heating incurred during separation, sympathetic cooling has been demonstrated in the ion trap system [26, 28, 29]. Thus the trap architecture does appear to be realistically feasible but more work is needed. For example, 'T'-junction structures [27, pp. 295-306] will need to be used in a large-scale device and these have not yet been demonstrated. Additionally, it will be desirable to further reduce the separation time to reduce the substantial overhead incurred by these operations.

III. DENSE CODING

Dense coding is a simple QIP protocol which demonstrates the potential application of entanglement in communication [30]. Consider two parties (Alice and Bob), that each share one qubit of a maximally entangled pair $\Phi^+ = |+Y\rangle_A|\uparrow\rangle_B + |-Y\rangle_A|\downarrow\rangle_B$. Here $|\pm Y\rangle$ are the eigenstates of σ_y $(\sigma_y|\pm Y\rangle = \pm|\pm Y\rangle)$ and the labels A and B are used to distinguish Alice and Bob's respective qubits. If Alice now operates on her qubit using I, σ_x, σ_y or σ_z the joint state is given by Φ^+, Ψ^+, Φ^- or Ψ^- respectively where $\Phi^\pm = |+Y\rangle_A|\uparrow\rangle_B \pm |-Y\rangle_A|\downarrow\rangle_B$ and $\Psi^\pm = |-Y\rangle_A|\uparrow\rangle_B \pm |+Y\rangle_A|\downarrow\rangle_B$. This is a complete (entangled) basis for the two qubit state-space. Thus if Alice then sends her qubit to Bob he can perform a measurement to unambiguously determine which operator Alice used. Each operator can be uniquely identified with two bits of information and so the transmission of one qubit facilitates the communication of two (classical) bits of information.

Demonstration of the dense-coding protocol with atomic qubits was reported in [8]. The initial entangled state was established quite straightforwardly using a joint $\pi/2$-pulse followed by an application of the phase-gate. Alice's single bit operation was then achieved using the individual addressing technique discussed above. Finally the detection step was implemented. First the joint state was rotated from the $\{\Phi^\pm, \Psi^\pm\}$ basis to the measurement basis $\{|\uparrow\uparrow\rangle, |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\downarrow\rangle\}$ using the phase gate followed by a joint $\pi/2$-pulse. Each qubit was then measured by separating the ions and detecting them individually. An average fidelity of 0.85(1) was achieved. Although not immediately applicable to communication, the demonstration is important in that it demonstrates multiple use of conditional logic gates, individual qubit measurements, and reliable separation of ions.

IV. TELEPORTATION

Quantum teleportation [31] provides a means to transport quantum information efficiently from one location to another, without the physical transfer of the associated quantum-information carrier. This is achieved by using the non-local correlations of previously distributed, entangled qubits. Teleportation is expected to play an integral role in quantum communication [32] and quantum computation [33]. Implementation of quantum teleportation is therefore an important benchmark for comparison of QIP in other physical systems. The demonstration at NIST [9] also incorporates most of the techniques necessary for scalable QIP in an ion-trap system [16, 34].

Previous experimental demonstrations have been implemented with optical systems that used both discrete and continuous variables [35–40], and with liquid-state nuclear magnetic resonance [41]. The demonstration at NIST [9] and at Innsbruck [10] are the first demonstrations of teleportation using atomic qubits. Aside from obvious differences in the experimental implementations the basic protocol is the same [31]. Alice is in possession of a qubit (here labelled 2) that is in an unknown state $|\psi\rangle_2 \equiv \alpha|\uparrow\rangle_2 + \beta|\uparrow\rangle_2$. In addition, Alice and Bob each possess one qubit of a two-qubit entangled pair that we take to be a singlet $|S\rangle_{1,3} \equiv |\uparrow\rangle_1|\downarrow\rangle_3 - |\downarrow\rangle_1|\uparrow\rangle_3$. Therefore, Alice possesses qubits 1 and 2, while Bob holds qubit 3. The initial joint state of all three qubits is

$$|\Phi\rangle = |S\rangle_{1,3} \otimes |\psi\rangle_2. \tag{3}$$

This state can be rewritten using an orthonormal basis of Bell states $|\Psi_k\rangle_{1,2}$ (k=1,2,3,4) for the first two qubits and unitary transformations $\{U_k\}$ acting on $|\psi\rangle_3$ $(= \alpha|\uparrow\rangle_3 + \beta|\downarrow\rangle_3)$ for the third ion. This gives $|\Phi\rangle = \sum_{k=1}^4 |\Psi_k\rangle_{1,2}(U_k|\psi\rangle_3)$. A measurement in the Bell-state basis $\{|\Psi_k\rangle_{1,2}\}$ by Alice then leaves Bob with one of the four possibilities $U_k|\psi\rangle_3$. Once Bob learns of Alice's measurement outcome (through classical communication), he can recover the original unknown state by applying the appropriate unitary operator U_k^{-1} to his state $U_k|\psi\rangle_3$. Alice's Bell-state measurement can be accomplished by

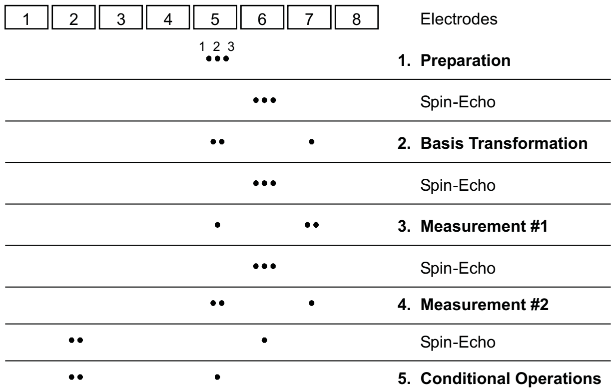

FIG. 2: Schematic diagram of the teleportation implementation using atomic qubits. Ions are numbered left to right as indicated at the top. In step 1, we prepare the outer ions in the singlet state and the middle ion in an arbitrary state. Steps 2-4 constitute a Bell-state measurement on ions 1 and 2, teleporting the state of ion 2 onto ion 3, up to unitary operations that depend on the measurement outcomes. In step 5 the conditional operations are applied, recovering the initial state. Interspersed are spin-echo pulses that protect the state from dephasing due to fluctuating magnetic fields but do not affect the teleportation protocol.

transforming from the basis $\{|\Psi_k\rangle_{1,2}\}$ into the measurement basis $\{|\uparrow\uparrow\rangle, |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\downarrow\downarrow\rangle\}$ as in the dense-coding experiment.

The NIST implementation of quantum teleportation is illustrated in Fig. 2 and a more detailed account can be found in [9]. Briefly, the three ions were first prepared in the state $|S\rangle_{1,3} \otimes |\downarrow\rangle_2$. This was achieved by first using a phase gate combined with global rotations to produce the state $(|\downarrow\downarrow\rangle_{1,3} - i|\uparrow\uparrow\rangle_{1,3}) \otimes |\downarrow\rangle_2$. Further global rotations and an individual addressing operation were then used to produce $|S\rangle_{1,3}$ from the state $|\downarrow\downarrow\rangle_{1,3} - i|\uparrow\uparrow\rangle_{1,3}$. For the state $|S\rangle_{1,3} \otimes |\downarrow\rangle_2$, ions 1 and 3 are in the singlet state, which is invariant to a global rotation. Therefore an arbitrary global rotation $R(\theta, \phi)_{1,2,3}$ applied to all three ions rotates the middle ion without affecting the outer two. This allowed the NIST team to produce the state $|\Phi\rangle$ of Eq. 3 for any α and β. Steps 2 to 4 constitute a Bell-state measurement on Alice's qubits (ions 1 and 2). In step 2, a phase gate and a $\pi/2$-pulse ($R(\pi/2, 0)$) applied to Alice's qubits effects a basis transformation from the Bell-state basis to the measurement basis, as in the dense coding protocol discussed above. The teleportation was completed by applying unitary operations on ion 3, conditioned on the measurement outcomes from steps 3 and 4. The unitary operators were simply a $\pi/2$-pulse ($R(\pi/2, \pi/2)$) followed by the operators $\sigma_x, \sigma_y, I, \sigma_z$ for the measurement outcomes $|\uparrow\uparrow\rangle_{1,2}, |\uparrow\downarrow\rangle_{1,2}, |\downarrow\uparrow\rangle_{1,2}, |\uparrow\downarrow\rangle_{1,2}$ respectively. In the experiment additional spin-echo pulses $R(\pi, \phi_{SE})$ were used to prevent dephasing due to variations in the ambient magnetic field on a time scale longer than the duration between pulses [5, 9]. Inclusion of such pulses does not fundamentally change the teleportation protocol; however, for $\phi_{SE} = \pi/2$, the operations following the $\pi/2$-pulse, $R(\pi/2, \pi/2)$, must be reordered to $I, \sigma_z, \sigma_x, \sigma_y$ respectively.

By teleporting a range of states ($|\uparrow\rangle, |\downarrow\rangle, |\uparrow\rangle \pm |\downarrow\rangle$, and $|\uparrow\rangle \pm i|\downarrow\rangle$), which cover the entire Bloch sphere, an average fidelity of 0.78(2) for the teleportation protocol was determined. This exceeds the upper bound of 2/3 for any classical protocol, which doesn't use entanglement [42]. Although teleportation has been demonstrated in other systems, the NIST demonstration incorporates teleportation into a simple experiment in such a way that it can be viewed as a subroutine of a quantum algorithm; a Ramsey experiment on two spatially-separated qubits. Furthermore, the NIST demonstration incorporates most of the important features required for large-scale quantum information processing using trapped ions [16, 34]: (a) qubits are reliably selected from a group and moved to separate trap zones while maintaining their entanglement, (b) manipulation and detection of qubits is achieved without the need for strongly focused laser beams, and (c) quantum logic operations conditioned on ancilla measurement outcomes are performed.

V. FUTURE OUTLOOK

The demonstrations of dense coding and teleportation in the ion trap system are encouraging and highlight the latest developments towards scalable QIP in this system. Although large-scale QIP is still in the distant future, it should not be overlooked that the techniques used may have more immediate application. The tools required for QIP have been used to investigate issues of decoherence in quantum systems [43] and to test the fundamental principles of quantum mechanics [15, 44, 45]. Experiments have also demonstrated potential improvements in frequency metrology [7]. As the development and control of the ion-trap system improves, it can be anticipated that new applications will found.

VI. ACKNOWLEDGEMENTS

This work was supported by the U. S. National Security Agency (NSA), the Advanced Research and Development Activity (ARDA) and NIST.

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Physics for the Nation: the Australian Institute of Physics Congress, 2005

The 16th Biennial Congress of the Australian Institute of Physics, which will be held in Canberra at the Australian National University from 31 January – 4 February, 2005, is likely to be the largest gathering of physicists ever held in Australia. The Australian Optical Society **Annual Conference will be held in conjunction with the Congress**

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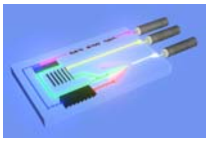
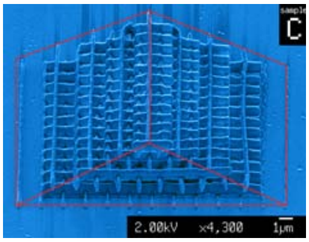
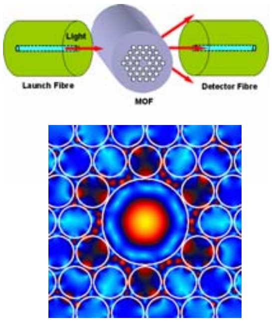
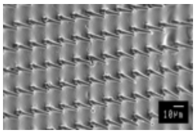


The aim of the **Microphotonics** project is to design, fabricate, characterize and model 3-D polymer-based photonic crystal structures. The demonstration of a photonic crystal superprism is of particular interest because of its startling optical properties.

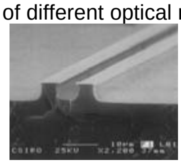


The **Micro-structured Optical Fibre (MOF)** project explores novel MOF designs for use in photonic device applications. MOFS are being explored for device applications and optical interconnects to provide efficient connections from standard single-mode fibers and planar waveguides.

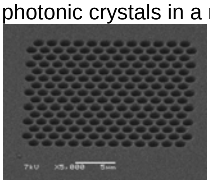




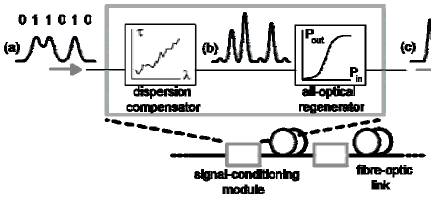
The **Laser Micro-Machining** project develops processes for laser-based micro-structuring of a range of linear, non-linear and high-gain optical materials, to produce photonic structures including waveguides in bulk glasses, 2-D photonic crystals and quasi phase matched crystals.



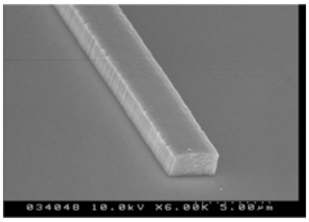
The aim of the **Photonic Integrated Waveguides and Circuits** project is to design, fabricate and characterise planar silicon optical waveguides and 2D photonic crystals in a range of different optical materials.



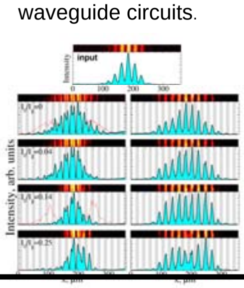
The **Optical devices and Applications** project develops all-optical signal processing functions including regeneration, wavelength conversion and amplification.

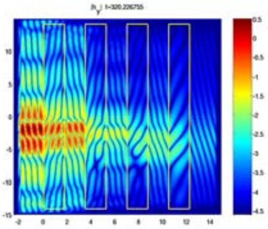


The aim of the **Non Linear Materials** project is to develop high nonlinearity chalcogenide glasses leading to novel nonlinear photonic devices including planar photonic crystals. .

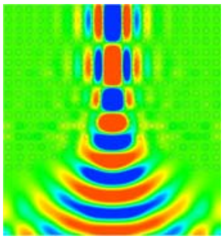


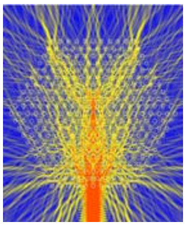
The **Non Linear Photonic Crystals** project studies the generation and propagation of nonlinear localized modes and all-optical switching in periodic photonic structures and waveguide circuits.



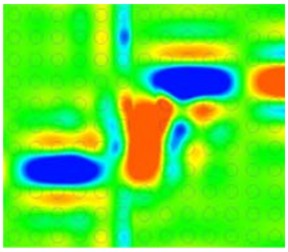


The **Computational Modelling** project provides computational modelling and visualisation techniques through generic modelling tools, new methods for modelling photonic structures and devices, and expertise in visualisation.

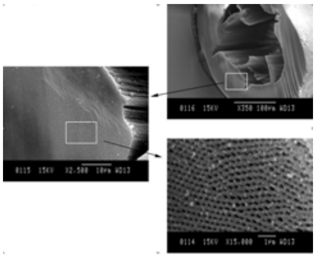




The **Photonic Circuits** project aims to find the best way to achieve tight guidance of light in optical circuits and to optimize photonic circuit features for Fresnel losses, radiation losses and impedance mismatches.



The aim of the **Radiation Dynamics** project is to explore radiation dynamics in microstructured photonic crystal materials. We aim to identify bandgap structures and use quantitative structural information to predict their optical properties.



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The Australian Research Council Centre of Excellence for Quantum-Atom Optics is one of Australia's contributions in the rapid development of quantum science that is happening around the world.

The Centre brings together scientists working in three cities, Australian National University (ANU) in Canberra, University of Queensland (UQ) in Brisbane and Swinburne University of Technology (SUT) in Melbourne and links them with scientific partners in Europe and New Zealand.

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

One area will be optics and wave affects of both light and atoms. Scientifically we are now able to investigate the quantum behaviour of larger objects, involving thousands and millions of atoms and see the transition from the microscopic world of a few particles to the macroscopic world of classical. Technically we are now able to use the concept of entanglement that was just a concept in the 1930s, and use it in practical applications, such as a communication system.

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The Centre concentrates on fundamental science questions. It combines our well-established track record in quantum optics with our leading groups in atom optics and laser cooling into one team with common goals. We are combining pioneering theoretical work with experimental projects.

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

The Centre congratulates Prof Peter Drummond from the ACQAO UQ Node on being the recipient of the Massey Media, a joint AIP-IOP prize for his work on many-body theories and quantum-optics, including his recent work on Bose-Einstein condensates, and novel features of solitons and quantum information in atom and optical lasers.

Congratulations also to Dr. Ken Baldwin, Deputy Director of ACQAO, awarded this year's Australian Government Eureka Prize for Promoting Understanding of Science.

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