THE AUSTRALIAN NATIONAL UNIVERSITY

SCIENCEWISE

Physics Special Edition

Australian National University

Welcome to the Physics Special

Physics is the study of the nature of the universe, from fundamental particles to large complex systems like planets and human beings. If you understand the basic building blocks of matter and force and how they interact, then in principle at least, you can understand everything. This continuous line of reasoning from basic concepts to complex systems is what makes modern physics such a rigorous, effective and powerful tool for shaping and understanding our world.

The Australian National University hosts one of the largest and most comprehensive physics research programs in the Southern Hemisphere. Some of this research is theoretical, such as string theory and various aspects of quantum mechanics. Some is highly applied materials science in semiconductors, lasers, detectors and their fabrication into novel devices. And yet more research focuses on the “big picture” modelling of hugely complex systems such as climate and turbulent flows in everything from plasma fusion reactors to bushfires.

In support of this diverse activity, ANU hosts extensive research infrastructure including: Australia’s largest accelerator the 14UD, the H-1 National Facility for plasma confinement, the ACT node of the Australian National Fabrication Facility and the Australian Positron Beamline Facility.

We have outstanding research leaders heading up our scientific programs and also provide physics education at the highest international standards. Our aim is to recruit the best and brightest of students at both the graduate and undergraduate level and to provide them with the best learning experience available. In doing so, we hope to ensure continued success in the future not just for our own university, but for the discipline of physics in general.

Whilst it’s not practical to cover all of the physics research at ANU in one magazine, I hope this collection of stories gives some sense of the quality and diversity of the work that goes on here and why in the 2012 Academic Ranking of World Universities (ARWU), ANU was the top placed physics school in Australia.

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Encryption for a cloudy day

How new quantum technology will ensure absolute data security – anywhere, anytime

When you log onto your bank's website, the data you send and receive is protected by encryption. To achieve this there are two key steps that need to be taken. Firstly a protected session key is created during link establishment. Secondly a password is used for user authentication. Essentially, the session key is combined with the data you enter to create a string of what looks like gobbledygook. At the other end the bank, knowing the key can divide the data by this to make sense of the transmission.

The problem with this system is that the security is based on mathematical factorisation tasks that are tedious but not particularly complex. If an eavesdropper intercepts the transmission he or she can, given enough patience and computer power, unscramble the signal and worse still, steal your password and use it.

With today's technology this is not a huge threat because the computer power necessary to crack current codes is not commonly available to individuals. But clearly it's only a matter of time before it is. One could combat a brute force attack by increasing the length of the encryption key but that's just buying time, not fixing the fundamental flaw in the system. By using a larger key you also affect performance as this increases delays for legitimate users when establishing a secure session.

Quantum data transmission security is fundamentally different. It's physically impossible to make a measurement on a quantum state without disturbing it. So for example if someone sends a single photon along an optical fibre and an eavesdropper measures its properties, the correctly equipped intended recipient would know that the data channel was compromised. The system is fool proof in that its security is hard-wired into the laws of physics. However single photon emission, detection and processing is hugely expensive and very slow so the technique doesn't really integrate well into the existing world of communications.

QuintessenceLabs is a new advanced technology company attached to the ANU developing second generation quantum communications systems. "When you get right down to it, secure communications underpins our economic prosperity," says Chris O'Neil, the chief marketing officer of QuintessenceLabs. "If your business competitors can access your product secrets, you're set to lose millions. But it's not just data in transit that's at risk. Data stored on company and government computer systems is a favourite target for hackers of all kinds and such attacks can and frequently do occur."

So how do you protect your data when it's sitting on a hard drive or worse still, stored in a distributed cloud environment where you have no idea where the actual hardware is or who has access to it?

> **"When you get right down to it, secure communications underpin our economic prosperity"**

Team discussion at QuintessenceLabs

The answer comes from physics and the concept of Quantum Key Distribution, QKD. If each parcel of data is encrypted by a unique key and that key changes constantly, no amount of number crunching can retrieve the data. Brute force attacks based on looking for a common factor in the data stream no longer work because there isn't one. What you have is mathematically indistinguishable from random noise. But to make this work, you need two additional components.

Firstly the key sequence needs to be truly random. If for example your key simply increments by one each time, the eavesdropper can look for that pattern. Pseudo random electronic number generators are better, but they still have underlying patterns. So the best possible security comes from truly random key sequences and that's what QuintessenceLabs systems use. Their key sequences are generated by the interaction of a laser with quantum vacuum noise and as such are entirely unpredictable.

The second component to make this all work is a secure method of transmitting the key. This has to be in the form of quantum entangled carrier particles, in this case photons in an optical fibre. But rather than the slow and expensive single photons, QuintessenceLabs have developed a bright laser variation that can be transmitted through normal fibre optic communications channels. Using a clever combination of quantum analysis and post processing of the signal they can detect how much of the signal has been lost and possibly eavesdropped. So long as the loss is not above a critical point, it's impossible for anyone listening in to reconstruct the key. And of course even if the loss exceeds that point, the system dynamically adjusts until the transmission completely ceases.

Now imagine you're a stockbroker with a lead on tomorrow's hot shares or an aerospace manufacturer with a design for a revolutionary new jet engine. Or even a government with details on the world's top 100 terrorists. You can quantum encrypt that data, send it to your partners on the other side of the world, even store it on a low cost cloud server in Africa and know that it's fundamentally 100% secure, today and into the future regardless of what technology does.

"Essentially that's our business model," Chris says, "To use advanced physics and mathematics to provide a cost effective and inherently secure service to our clients. And to do so in a way that integrates seamlessly into the existing framework of computing and telecommunications."

Something to reflect on

Nanotechnology largely eliminates reflection waste from solar cells

The average solar cell that you might see on the roof of a house has an efficiency of about 10 to 15%. That is, only about one in ten of the photons of sunlight striking it are converted into electrons of usable electricity. To a large extent this limitation is set by the inherent properties of the silicon that such cells are made of. In recent years scientists have been looking at ways of improving this situation by using other semiconductors to create cells and even sandwiches of several materials each able to absorb a part of the solar spectrum that the ones above can't.

One class of semiconductor frequently used in efficient solar cells is the III-Vs. Compounds like gallium arsenide GaAs, that have one atom from group three of the periodic table and one from group five. Using III-V cells, efficiencies of over 40% are possible when the cells are coupled with external optical concentrators.

However even III-V cells are limited by two fundamental physical processes. One is reflection from the surface. Semiconductors have very high refractive indices which means that incident light is reflected far more strongly than it would be from glass or plastic. As much as 30% of the sunlight can be lost in this way.

The second problem relates to the junction. Solar cells are made from junctions between an n-type semiconductor in which electrons are the predominant carrier of electricity and a different version of the same material in which holes carry the charge – so called p-type material. The physics of the p-n junction dictate that there are essentially no charge carriers at all in the junction region which can range from nanometres to microns in size. When a photon of sunlight hits the junction an electron and a hole are created which rapidly migrate to the n and p type material respectively thus creating a current in the external circuit.

The problem for a cell designer is that there are competing requirements in the size of this active junction. The wider the junction the more photons will be absorbed in it. But a wide junction also means a long journey for the electrons holes and a greatly increased chance that they will recombine with each other inside the junction yielding no external current.

However recent work at the Australia National University may be set to change the rules on how cells are made by making clever use of nanotechnology. Associate Professor Hoe Tan leads a group specialising in the growth of exotic structures in III-V semiconductors. "We've been adapting nanowire growth technology to produce solar cells." Professor Tan says, "Because the physical properties of nanowires should enable us to solve the twin problems of reflection and junction absorption."

Essentially the nanowire cell consists of countless ultra thin projections from the surface of a conventional semiconductor wafer almost like fur on animal skin. Each wire is several µm long but only a few 10's of nanometres wide. The core of the wire can be grown p type GaAs whilst the cladding n type so in effect each wire is a coaxial p-n junction.

The light trapping properties of the nanowire arrays reduces reflection to a tiny fraction of that from a solid chunk of GaAs with light reflected from one wire being absorbed by one of its neighbours. Likewise the microscopic coaxial junction leaves very little room for recombination loss since electrons or holes have to travel only a few 10's of nm to the contacts.

"Making nanowire junctions isn't the same as making conventional solar cells though," Professor Tan explains, "Once we have the nano structure there are quite a few steps involved in creating the final cell."

The fine "fur" of nanowires is mechanically delicate so it has to be planarised – that is turned into a single solid mass by the addition of a polymer that fills the caps between the wires. The polymer is plasma etched back to expose the ends of the wires so that a transparent electrode can be applied to allow transmission of sunlight to the nanowires and draw off the electric current.

"We've been experimenting with several polymers some of which even enable us to peel off the nanowire cell layer right off the underlying wafer." Professor Tan says, "So in effect what we are creating is a flexible nanowire solar cell that you can wear."

In their flexible or rigid forms these new cells are attracting lots of interest from those to whom efficiency really matters such as space engineers and designers of large scale solar concentrator power farms. "If you are building a concentrator system chances are you're investing a lot of money, "Professor Tan says, "So generally you're going to want to use the most efficient cells at the focal point of the concentrator even if they're a bit more expensive than silicon cells. Additionally, III-V semiconductor materials are able to withstand much higher solar concentration ratios than silicon."

The nanowire solar cell grown on the lower wafer has vastly lower reflection loss than the conventional cell above

Pinching the plasma

Developing advanced materials to solve the energy crisis

The world is facing an energy crisis as increasing population and urbanisation consume fossil fuels at an exponential rate. Aside from their undesirable carbon footprint, fossil fuels like oil also look set to run out within this century. To make matters worse, recent events in Japan have deeply shaken public confidence in the nuclear industry and humanity's ability to deal with the highly toxic waste from conventional fission reactors.

However amidst this rather gloomy picture there is some positive news. International efforts to harness fusion power – the process of fusing two hydrogen-like nuclei to create helium – are well in progress. The world's first practical fusion power plant ITER is currently being built in Southern France by an international scientific consortium.

It is projected that ITER will generate 500 megawatts of power whilst requiring only 50 megawatts to create the plasma. Its fusion reactions will emit no greenhouse gasses and perhaps most importantly, will generate no long lived radioactive waste to pose a contamination threat to the environment. However, the technological challenge of designing and building such a device is daunting.

One particularly challenging aspect of designing a reactor like ITER is finding a suitable material for the walls of the reaction chamber. Although the pressure inside is low and the intensely hot plasma is kept out of physical contact with the wall by the magnetic containment field, energetic by-products of the fusion process irradiate the wall with great ferocity.

Such energetic particles smashing into materials like metals create two problems. Firstly the impacts degrade the wall material by both chemical reactions and by sputtering atoms out of the wall like a snooker ball hitting the pack. Secondly, these secondary atoms and ions that are sputtered out of the wall mix with the fusion plasma disrupting the flow and cooling it, both effects being detrimental to the efficiency of the reactor.

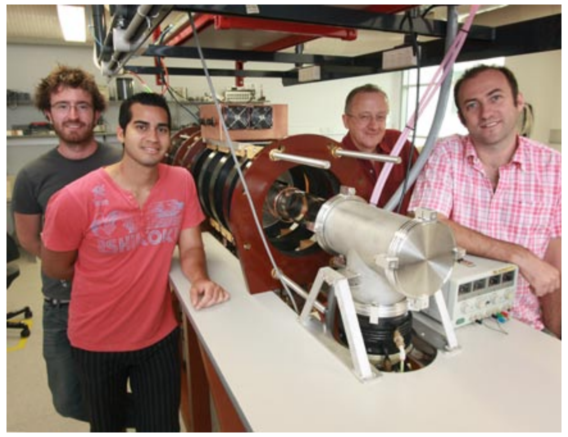
One scientist working on just this problem is Dr Cormac Corr who heads up the Plasma Surface Interaction group within the Plasma Research Laboratory at the Australian National University. "Really this boils down to a materials science problem," Dr Corr explains, " We need to develop new exotic materials that can better withstand these extreme environments." Dr Corr's research applies a helicon generated plasma system, initiated and designed by Dr. Boyd Blackwell in collaboration with colleagues from Oak Ridge National Laboratories, which can mimic the incredibly harsh conditions experienced inside a fusion reactor.

This prototype plasma system known as the Material Diagnostic Facility, MDF, generates a very high-density hydrogen plasma which is then accelerated towards the material test target. Looking something like a ray gun from a Flash Gordon movie, the MDF uses a series of magnetic coils to create a field gradient called a magnetic focus that acts like a lens on the plasma stream. Just as an electron microscope focuses electrons onto a sample, the magnetic field focuses the plasma beam into a single intense energetic spot. This mimics the very conditions that will exist at the internal walls of fusion reactors of the future.

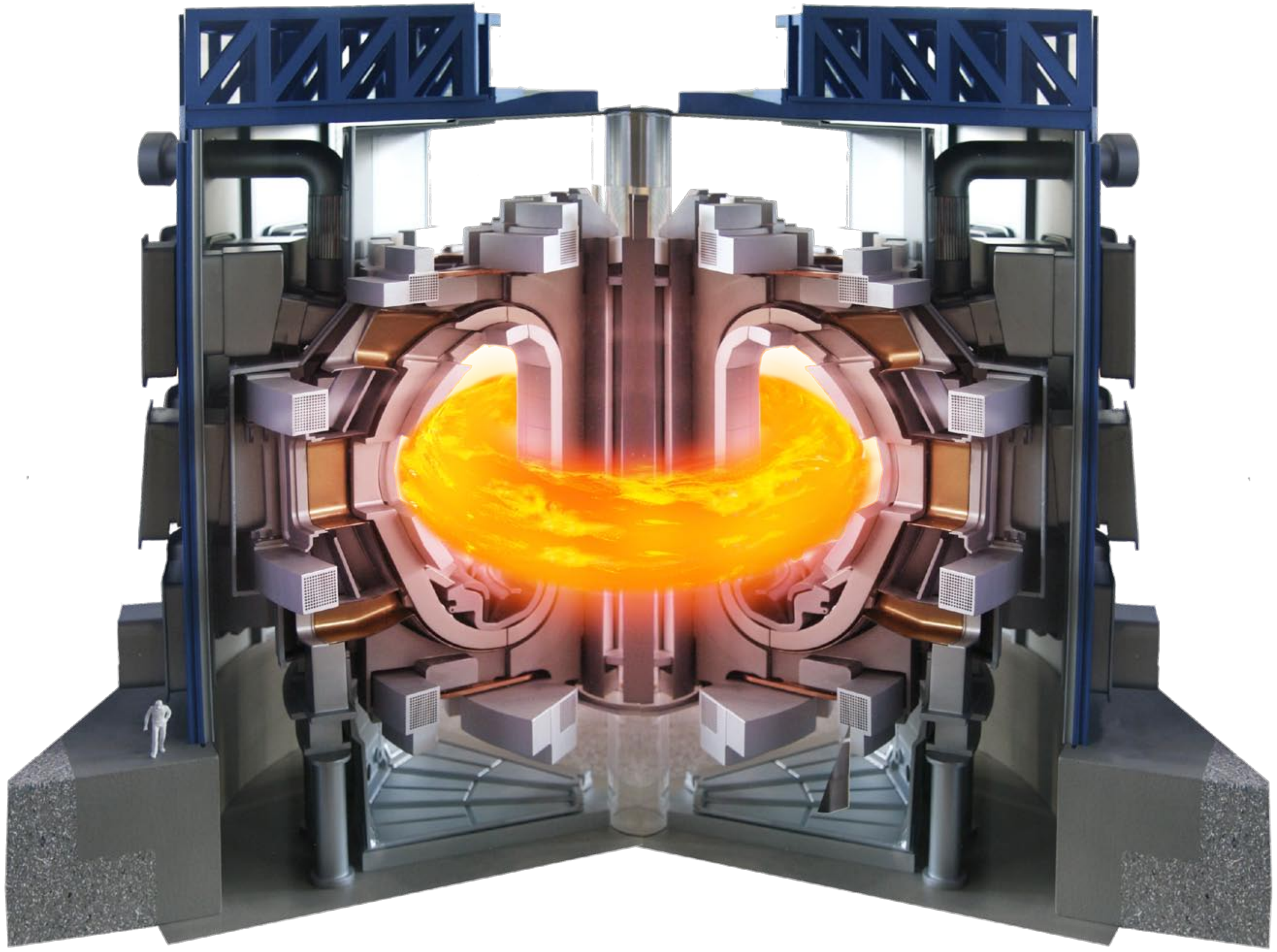
"Essentially we're trying to unfold the synergistic effect of plasma and ion bombardment at the plasma-wall interface. We want to do that in a controlled environment in which we can use advanced diagnostics to really understand the underlying science of what's going on." Dr Corr says.

The diagnostics on the MDF include optical spectroscopy and sophisticated ion probes that give scientists information on the types of particles sputtered out, their energy and how they are interacting with the plasma in the chamber. The MDF is a part of the Australian Plasma Fusion Research Facility, available to researchers through the Australian Institute of Nuclear Science and Engineering (AINSE) or by collaboration with Plasma Research Laboratory staff.

As part of the recently announced collaborative agreement between ANU and ANSTO, researchers at the Institute of Materials are providing materials research expertise and developing a target chamber for MDF.



Some members of the research team, Cameron Samuell, Juan Caneses, John Wach and Dr Cormac Corr



"Advanced materials is an area in which Australia can really make a significant contribution to the international fusion efforts," Dr Corr says, "Using the expertise here and at ANSTO we have the capability to develop smarter, better materials for such harsh environments." "It's difficult to predict the outcome of research, but we're hoping that we might be able to develop materials whose properties actually improve when irradiated perhaps even self organising or self repairing."

Of course fusion power is by no means the only application for such materials. Spacecraft and satellites are constantly bombarded by the energetic particles in the solar wind and frequently suffer damage as a result. Such better radiation resistant materials may also lead to longer, better and more ambitious space missions.

Fusion reactors such as the European ITER, promise vast quantities of electrical energy with zero greenhouse gas emission and no long lived radioactive by-products. The sheer size of ITER can be gauged from the man standing in the bottom section of the reactor.

Heavy metal

Scientists discover radically new form of aluminium

Many common materials behave in extraordinary ways when subjected to extreme temperatures and pressures. For example the common barbeque gas propane becomes liquid when pressurised in gas bottles. Under the far more extreme pressures found at the centres of stars, gaseous hydrogen adopts a metallic state.

Theoretical physicists have for many years predicted that if subjected to sufficient pressure the common metal aluminium can change its crystal structure from the normal face centred cubic (FCC) to a denser body centred cubic (BCC) form. Crystal structure matters a lot when it comes to chemical and physical properties, graphite, and diamond are both forms of pure carbon, yet their properties could hardly be more different. Theorists predict that aluminium with a BCC structure would be 41% denser than the FCC metal and may have vastly different chemical and physical properties.

Generally when physicists want to study what happens to materials under extreme pressures they use a device known as a diamond anvil. This is a specially shaped pair of diamond points that can be set in the jaws of a large hydraulic press which generally also has a facility to heat the compressed material. However diamond - the strongest material available - yields below the pressure and temperature required to transform aluminium. As a result no one has ever created BCC aluminium until now.

A international team including scientists at the Australian National University have just released a paper in Nature Communications in which they have created BCC aluminium by an unusual method they describe as a top down temperature and pressure approach. Instead of a mechanical squeezing device, they used an ultrafast pulse laser to create a plasma.

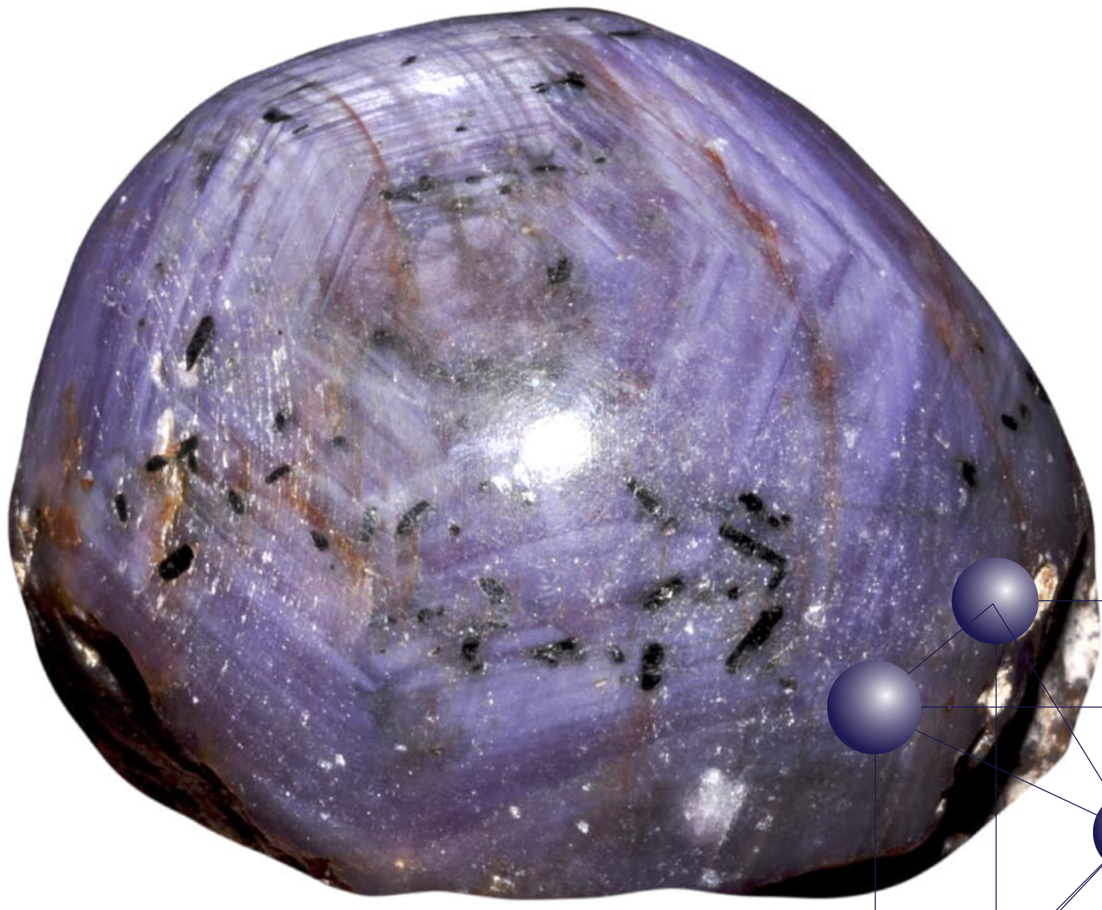
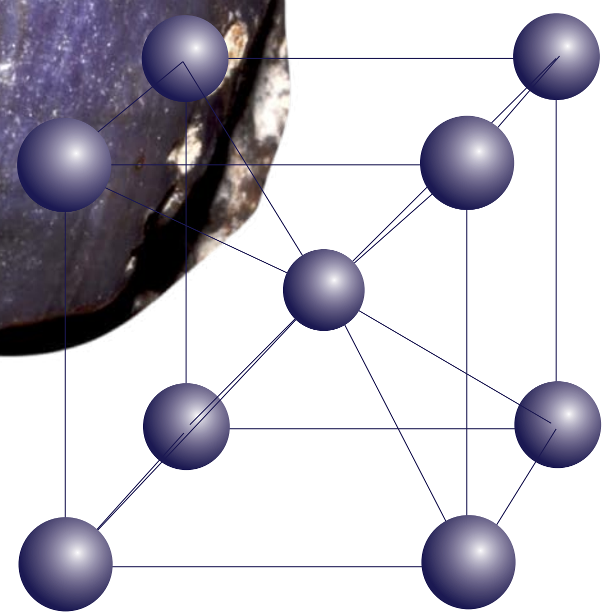
When using lasers to heat matter, the pulse length is of critical importance. A given amount of energy spread over a long pulse, heats the electrons and ions of the crystal relatively slowly allowing the heat to be transported from the focus by electrons and vibrations of the lattice known as phonons. As a result, an area far larger than the focal spot gets heated. However if the energy is concentrated into a short enough pulse – a few femtoseconds – the heat conduction mechanisms can't remove it from the focus in time and the result is a massive heating of a tiny area deep within the crystal.

This heating turns the material of the crystal into plasma which expands with colossal force, compressing the atoms of the crystal around it. By using a sapphire, which is an oxide of aluminium, the team were able to generate conditions of such extreme pressure and temperature that tiny shells of BCC aluminium were formed within the crystal. "It's not just the speed of heating that's important here, the material also quenches or cools very rapidly, freezing in a new phase." Professor Rode explains. "The pressures involved are enormous, over 50 million atmospheres."

At present the new metal only exists in tiny crystals, about 20 nanometres across within the compressed sapphire. However, new materials are always exciting to scientists and engineers because they offer the potential for better devices that can do things that were previously impossible. And the ultra fast pulse laser method offers a relatively simple way to make those materials.

There's also a lot of excitement about work like this from a pure physics point of view. Generally scientists don't have access to conditions like the centre of planets and stars in the laboratory. Moreover having the ability to create such ultra high pressures relatively easily using fairly small scale equipment offers the exciting potential of opening up this field of study.

"Knowing how materials behave under extreme pressures and especially having them available in the lab to study is a really helpful step in better understanding extreme physics such as that at the centre of the Earth as it was forming." Professor Rode says.

The scientists created the BCC aluminium inside a sapphire (aluminium oxide) crystal

Lighting the fire

How mathematical modelling may be the key to successful fusion power

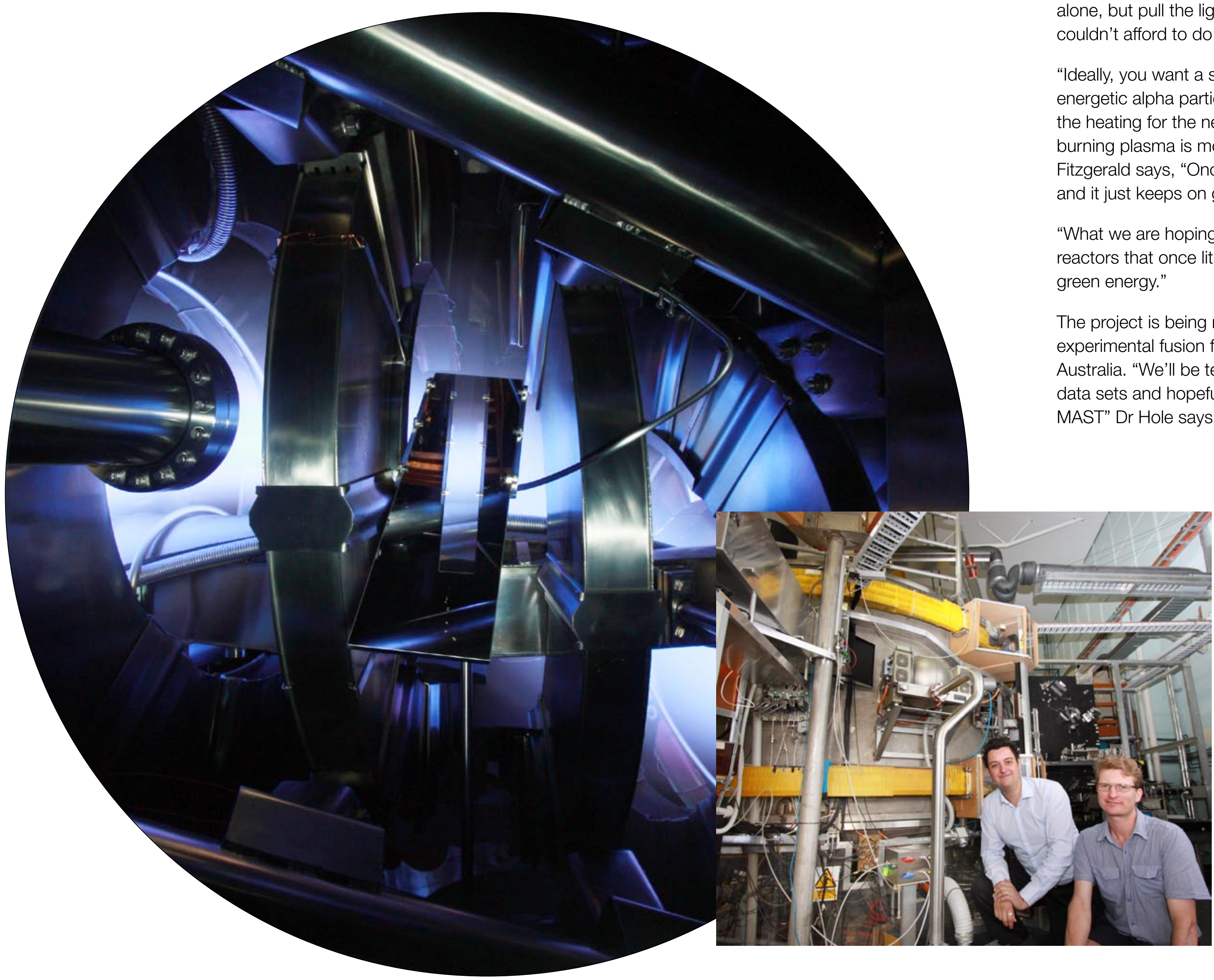
The air molecules in a room move constantly, colliding with each other, the walls and anything else that happens to be in there. The velocity of these molecules is what gives the air its temperature, the faster the motion the hotter the air. However not all the molecules are moving at the same speed. They follow what's known as a Maxwell-Boltzmann distribution, a bell curve of velocities that mathematically describes most fluids in equilibrium. The physics of fluids with such Maxwellian temperature distributions is well established and models many ordinary every-day fluids extremely well. However when it comes to more complicated situations such as the flow of super high temperature plasma in a fusion reactor, it begins to fall down. Dr Mathew Hole and Dr Michael Fitzgerald are two scientists aiming to put this right.

"Most of our existing theoretical models of plasma fusion reactors rely to a greater or lesser extent on simple Maxwellian distributions," Dr Hole explains, "But in a fusion reactor we know that there are times when the distributions are far from Maxwellian." This is because of the extreme conditions within a reactor and the fact that unlike many fluids, plasma is electrically charged.

Fusion can only take place when the plasma reaches a temperature of many millions of degrees and the only way to hold something that hot is within a magnetic bottle. The problem is that you can't get it that hot without using powerful microwave fields and injected beams of super energetic particles. Both make the plasma non-Maxwellian, and the introduced hot particles generate their own magnetic fields as they twist and weave along an externally applied magnetic containment field. The beam particles also inject momentum, spinning up the plasma. Now add to that the additional magnetic and electric fields generated by charged energetic alpha particles produced by fusion reaction, and you have mathematician's nightmare.

Unfortunately, there's no way round creating a solid theoretical model of any potential reactor. Such undertakings are multi billion dollar affairs so you can't make one on a "suck it and see" basis. If after ten billion dollars and ten years construction you realise it should have been a different shape or used a different metal in the walls, your credibility and finances are blown. As a result, governments and scientists alike, are very interested in improving the theoretical models on which the designs are based.

"What our project is looking to do is put theoretical modelling of plasmas on a more solid footing by building a mathematical model that isn't simply Maxwellian. We hoping to do this either by incorporating multiple fluids representing different energetic populations, and/or allowing those fluids to be anisotropic." Dr Hole explains.



Dr Mathew Hole and Dr Michael Fitzgerald with the H1 plasma confinement facility at ANU - Inset, a view through one of the observation ports of the plasma circulating within H1

An anisotropic fluid is one in which its properties such as pressure or temperature are different in one direction from another. "Think about a swimming pool," Dr Fitzgerald says. "When your head gets to the bottom your ears begin to hurt because of the pressure. It doesn't matter which way your head turns, the pressure's the same. That's an isotropic fluid."

"Now imagine you're underwater in a pool and someone's squirting a hose into your ear. You'd feel pressure in your ear one way but when you turn your head sideways, it's gone – at least from your ear. That's an anisotropic fluid, and that's very much more like the situation in a fusion reactor when the energetic heating beam is injected."

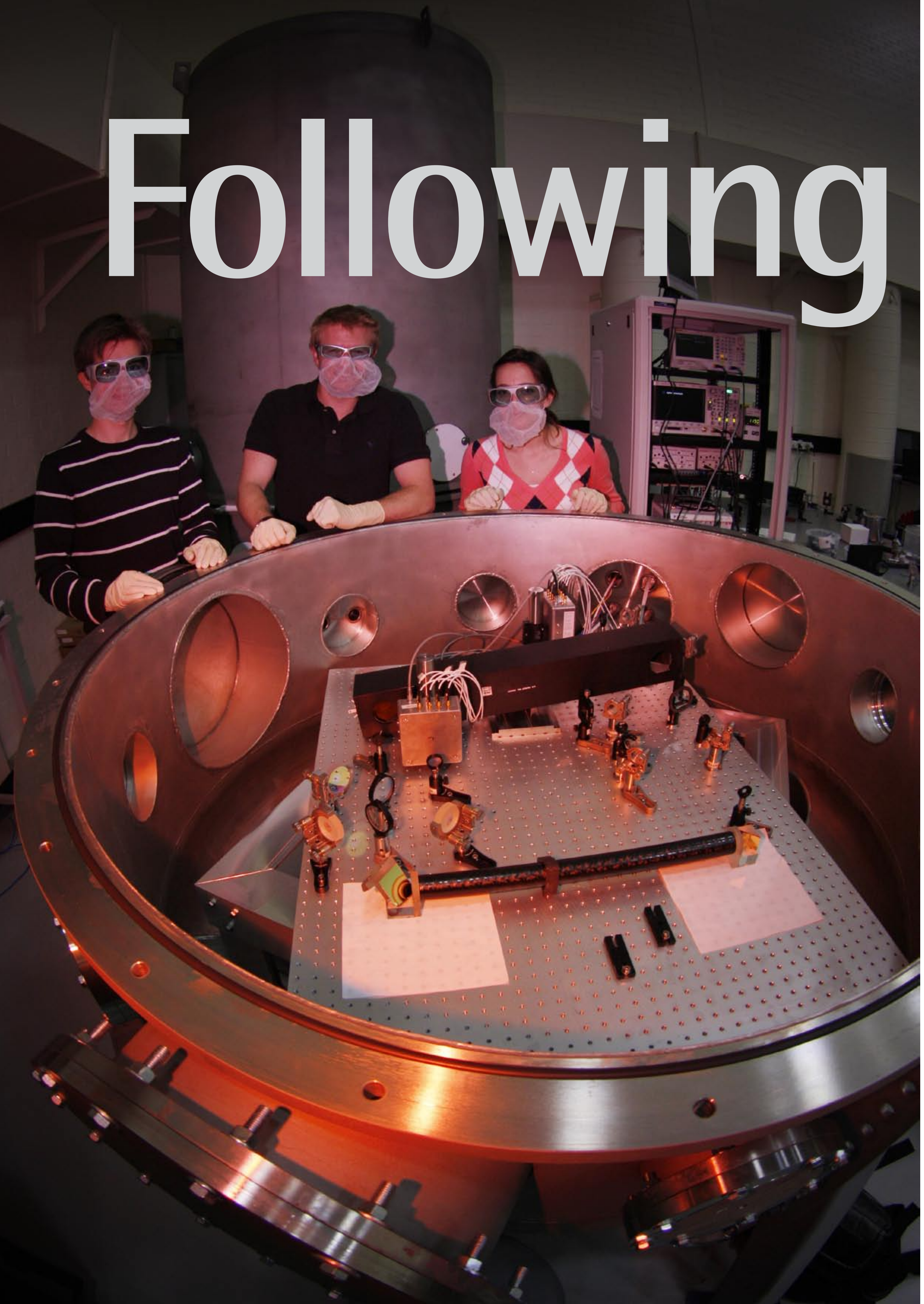
Although a heating beam is a great way to get a fusion plasma up to temperature, it's not desirable to keep it running all the time because it's highly expensive. Dr Fitzgerald draws analogy with a campfire. "Imagine making a campfire out of something like tea bags. If you hold your lighter under them they will burn, and you might do better keeping warm than with just the lighter alone, but pull the lighter away and it will just smoulder out. You couldn't afford to do that, you'd waste hundreds of lighters."

"Ideally, you want a situation where once up to temperature, the energetic alpha particles produced by fusion reactions provide the heating for the new fuel – a so called burning plasma. "A burning plasma is more like a campfire made of sticks," Dr Fitzgerald says, "Once it's well lit you can take the lighter away and it just keeps on going by itself."

"What we are hoping to do is improve the physics basis for reactors that once lit will simply pour out vast amounts of clean, green energy."

The project is being run in collaboration with the MAST experimental fusion facility in the UK and H1-NF facility here in Australia. "We'll be testing our models against known real world data sets and hopefully tuning them to the conditions inside MAST" Dr Hole says.

Following GRACE



Australian space technology to monitor groundwater

Agriculture constitutes a very significant part of Australia's economy and with the rising world population, food production looks set to become an ever more important part of what we do. However in spite of Australia's good weather and abundant land there is one constant threat to farming and that's the variability of our water supply.

In the good years there's plenty to go round but all too frequently rainfall is low and we rely increasingly on groundwater for irrigation. The trouble is no one's really sure just how much groundwater there is and at what rate it's depleted and refreshed.

It's not an easy thing to measure. Sure, you can drill a hole and see if there's water there. But is it ancient water or relatively newly fallen rain? Is it flowing from one area to another? And perhaps most importantly are we using it too quickly or could we safely use more and boost production?

NASA, the German Space Agency and the Australian Space Research Program are currently looking to answer just those questions and many others using a pair of satellites that map local variations in gravity. The mission is known as the Gravity Recovery and Climate Experiment or GRACE and has been gathering data since 2002.

Associate Professor Daniel Shaddock from the Australian National University leads a team that are developing instruments for the next mission, GRACE Follow-on. "GRACE has given scientists a vast amount of data which has provided a real insight into the changes in groundwater and ice across the globe" Professor Shaddock says, "The original satellites are now coming to the end of their service lives so we're working on the development of their replacements."

Measuring gravity is a bit more complicated than it might at first appear. On the ground all you need is a known mass and an accurate balance. It's possible to make a gravity map by walking your balance across the landscape but that's not really a very practical method to map an entire continent.

For a spacecraft crossing a continent is just a few minutes work. But a mass and balance system won't work on a satellite because an orbiting spacecraft is effectively in free fall, so anything inside it is weightless.

Dr Roland Fleddermann, Danielle Wuchenich and Professor Daniel Shaddock in the gravity wave lab preparing to optically test the GRACE Follow-on retroreflector

Following GRACE continued...

The twin GRACE Follow-on satellites will orbit the globe 200km apart. The ranging laser beam has to be reflected back with incredible accuracy if the signal is to be received back at satellite one. That's the job of the retroreflector optical arm seen at the left here

The characteristics of the craft's orbit are however influenced by the gravity of the Earth below. Imagine if the Earth were to suddenly get twice as massive. All the satellites currently in orbit would be pulled into lower orbits. If the Earth's mass halved they'd swing further out into space. Local variations in gravity are of course, not even remotely on that scale, but the effect is the same. Fly over something heavy on the Earth's surface like a mountain and the satellites will wobble very slightly.

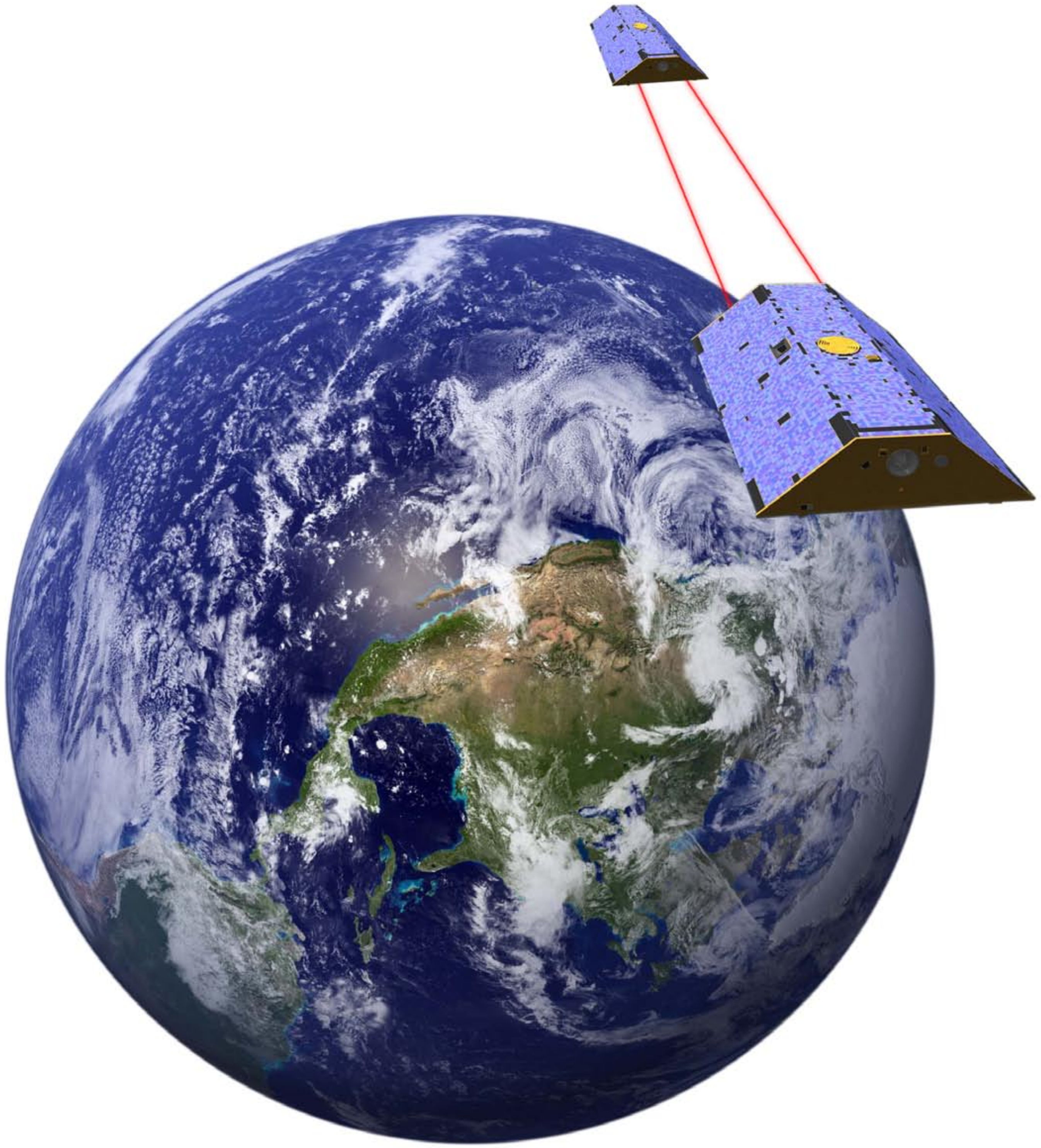
"It would in principle, be possible to simply have a single satellite orbiting the Earth and monitor its position from the ground." Professor Shaddock says, "But the tracking equipment would have to slew rapidly across the sky and you'd need multiple identical stations round the globe. The atmosphere also introduces problems with the ranging signals. However, if you have two satellites in space, you get round all those problems because one acts as the ranging station for the other."

The two GRACE satellites, aptly nicknamed Tom and Jerry, chase each other across the sky about 200km apart and about 500 km above sea level. Because the lead satellite flies over gravitational anomalies first, its distance to the trailing satellite changes slightly as its orbit is perturbed.

"On the existing mission this distance is measured using microwaves." Professor Shaddock explains, "But we can achieve far greater accuracy with optical wavelengths."

GRACE Follow-on will carry identical microwave instruments to the original, partly because the technology is proven and partly because it will help scientists get consistency between the old and new data sets. But in addition GRACE Follow-on will have a laser interferometer range sensing system that will be able to measure changes in the distance between the satellites of less than a ten thousandth of a millimetre.

One of the difficulties with this technique is that spacecraft tilt and rotate about their centre of mass slightly in flight. If you measure from an arbitrary point on the outside casing, this will distort the data because as it turns, the spacecraft corners get closer or farther away even though the centre of mass hasn't moved. "Ideally we'd like to have a laser and detector at the centre of mass of one satellite and bounce that beam off a reflector fixed at the centre of mass of the other, "Professor Shaddock says, "But that's not possible due to other design considerations."



To get around this the team have designed a retroreflector system that bends the light around the spacecraft in such a way as to simulate a corner cube reflector placed at the centre of mass.

The prototype system was built at CSIRO's Australian Centre for Precision Optics at Lindfield in NSW, with help from German collaborators. "We're currently in the process of testing the prototype to ensure that it meets all the optical specifications, "Professor Shaddock says, "Then the next step is to literally shake it up. We have to ensure that this and any other instruments that will hitch a ride into space on top of a rocket can withstand the considerable violence of the launch."

Local Canberra aerospace company EOS Space Systems will perform these so-called "shake and bake" tests before delivering the finished prototype to Germany at the end of the year.

What the scientists learn from this prototype will be used to construct the actual mission instrument which is scheduled to fly in 2017.

"We're really excited to be part of this mission, "Professor Shaddock says, "The new instruments should be able to give us data with unprecedented precision." However it's not just a matter of mapping the gravity variations round the Earth. Interpreting that data is a daunting task in itself.

Changing groundwater and ice thickness affect the local gravity a little. But other factors such as the height of the terrain and the Sun and Moon's gravity affect it hugely more.

"One of the key tasks in this mission is processing the data to eliminate other gravitational effects, "Professor Shaddock says, "Getting better measurements will be good but then it's up to the guys working on the data processing to figure out ways to sufficiently eliminate all the other gravity effects in order to really make best use of that extra precision. And that's a really difficult task."

GRACE has already provided excellent insights into the behaviour of ground water in Australia and across the globe. GRACE Follow-on, will build on that data set so that we will have an even better idea of what's happening to Australia and how best to manage our resources to ensure that our agricultural economic momentum isn't lost.

For those who wonder why a country built on primary production should spend money on fundamental physics research – this is one example of exactly why we should!

Helicon healing

Plasma physics finds novel applications in medicine

Nosocomial Infections are those acquired whilst being treated in hospital for other conditions and are of very serious concern to the medical community. They are one of the major causes of death in hospitals, accounting for almost 100,000 annual fatalities in the USA alone.

Although hospitals are kept scrupulously clean, the concentration of so many sick people tends to bring in a massive number of micro-organisms. The first line of defence against serious infection is of course antibiotics, but the problem is that the more these drugs are used, the more resistant strains begin to emerge and therefore the less effective they become. Whilst new antibiotics are being developed all the time, there's clearly a need for additional strategies to combat bacteria. One of the most recent to emerge has rather unlikely origins in a plasma physics laboratory.

Dr Christian Sarra-Bournet is a physicist working at the Australian National University in the Space Plasma, Power and Propulsion laboratory (SP3). "I was interested to explore alternative methods of treating bacterial infections especially nosocomial infections," he says, "Surprisingly enough there are some really strong links between materials with antibacterial properties and plasma processing."

Titanium Dioxide TiO_2 is most well known as the white pigment used in paints, but it has many other interesting properties. In its crystalline form, TiO_2 is a semiconductor that exhibits some extraordinary photocatalytic properties. When ultra violet light shines on a TiO_2 crystal, it generates electron-hole pairs, which can migrate to the surface to serve as a source of free electrons and electron absorbers. These form the basis for oxidation and reduction reactions, which can in turn create free radicals which attack the cell wall of bacteria, ultimately killing them. But the great thing about TiO_2 is that it's relatively harmless to human tissue, it is even used in sunscreen as a UV absorber.

"One of the limitations of TiO_2 is that its large band gap requires ultra violet light to generate the electron hole pairs," Christian explains, "So what we wanted to do was devise a method of generating a doped version that would work in visible light and also be economical to produce."

The method Christian chose was a process known as Helicon Assisted Reactive Sputtering, HAReS. This involves creating a plasma of oxygen and argon ions and using it to sputter material from a Titanium metal target. The sputtered titanium and oxygen vapour reacts in its plasma phase to create TiO_2 whilst the argon provides a dense and effective plasma and because of its inert noble gas properties, it doesn't get in the way of the chemistry. By adding nitrogen to the plasma, Christian was able to create TiO_2 doped with nitrogen atoms that was sensitive to visible light.

"In an environment like a hospital, there isn't that much ultraviolet light about, so by creating a material with the same antibacterial properties that's sensitive to visible light, we have something much more practical."

But the antibacterial properties of TiO_2 are not where its medical usefulness ends. TiO_2 is an excellent biocompatible material and possesses bioactive properties: when TiO_2 is exposed to fluids within the body, it will form a layer of Hydroxyapatite, a calcium mineral that accounts for about half the mass of human bones.

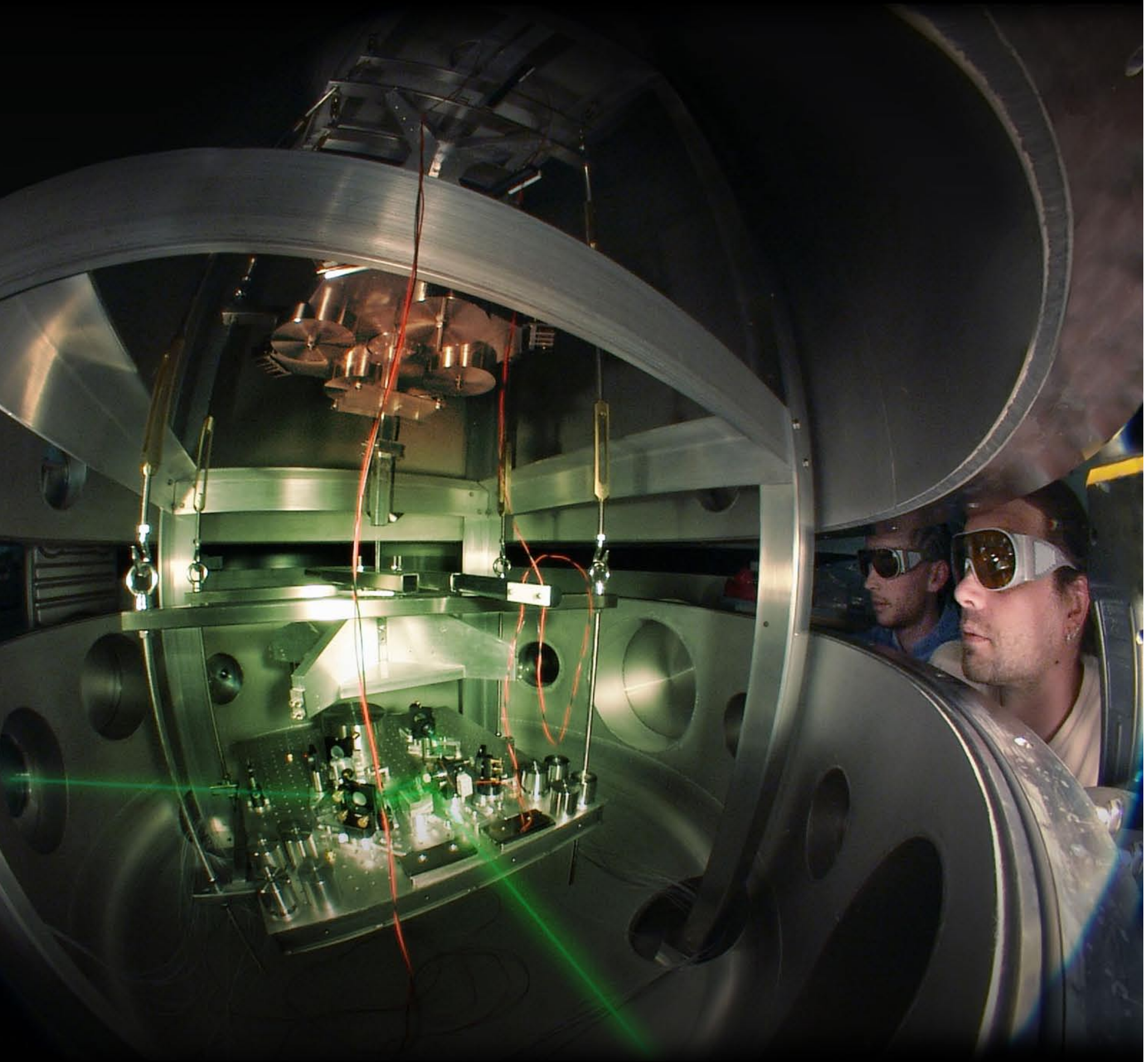
For this reason, prosthetic bone implants such as replacement hips and knees are often given a TiO_2 coating to enable them to bond strongly with living bone. The current method of producing this coating uses wet chemistry to deposit a thin layer then an annealing step at high temperature to give the TiO_2 its crystal structure. Whilst this works fine on metal parts, the high temperature excludes its use for polymers, fabrics and other heat sensitive parts of medical implants.

One of the advantages of Christian's technique is that the whole process is performed at room temperature, the crystallization being a natural result of the plasma/surface interactions while the semiconductor coating is being slowly deposited. Another advantage is that by varying the plasma conditions, it's possible to incorporate nitrogen or other elements and influence where they lie in the resulting crystal. "We've seen that the visible absorption, bioactivity and photocatalytic properties of the coatings are dependent not only on the amount of dopant but also whether the dopant replaces oxygen in the TiO_2 structure or lies in one of the interstitial sites of the structure. Plasma processing allows us to fine tune the material properties."

"This gives us a really powerful technique to produce coatings on medical implants that are not only effective in integrating with living bone tissue, but that also have natural antibacterial properties."

"It's a really elegant system," Christian says, "With which we can tailor the TiO_2 coating to suit a wide variety of needs ranging from bone implants to surgical tools and perhaps even nurse's uniforms."

Shaking the Universe



In search of gravity waves

Every now and again something calamitous happens out there in space. Stars undergo massive supernovae explosions or two black holes collide. Physicists believe that such massive acts of violence literally send ripples across the universe in the form of gravitational waves - perturbations of space-time itself.

Einstein predicted gravitational waves over 90 years ago but to date, no one has directly observed one. Their detection would open a new window for astronomy giving us a completely new way to probe the universe – akin to a deaf person being able to hear sounds for the very first time.

The reason Gravitational waves have proved so difficult to detect is that in spite of their violent origins, their impact on Earth based detectors is incredibly small. The change in the shape of space as a wave passes by is smaller than a million, million, millionth of a metre. And movements on that scale are incredibly difficult to measure.

Instruments currently operational, such as the Laser Interferometer Gravitational Observatory (LIGO), are within a factor of 10 of the required sensitivity. However with conventional detectors, most signals would be masked by the inherent quantum noise in the interferometer.

Facilities, like LIGO are already both expensive and physically huge. Increasing the size by a factor of ten or a hundred is out of the question. So scientists need to look at ways to do better with what they have. And one of those ways is to try to get round that problematic quantum noise on the laser.

That's exactly what scientists like Professor David McClelland of the ANU Centre for Gravitational Physics are doing. "You can't simply eliminate quantum noise in the way you can eliminate interference in electronics because it's a fundamental property of the light. That's just the way the universe is put together. But what you can do is use the Heisenberg uncertainty principle to decrease the quantum noise in one parameter of the light at the expense of increasing it in another. Then make your measurements using the less noisy parameter."

This technique is known as ***squeezing the light*** and is a speciality of the ANU group. It's rather like trying to squash a balloon: it gets smaller in the direction you're squeezing but expands elsewhere.

Over the past decade, Professor McClelland's group have been building a gravity wave laboratory in which to develop the squeezed light interferometer parts. This has required the construction of huge seismically isolated tanks in which prototype instruments are isolated from vibration in the environment by 200dB. To put that into perspective, it's like wearing earplugs that make a jet engine exhaust sound a thousand times quieter than a snowflake falling.

Having eliminated all the physical sources of vibration, the scientists are able to detect the minute buffeting of the mirrors caused quantum vacuum fluctuations. "This quantum buffeting may set a limit on the sensitivity of gravity wave interferometers at low frequencies," Professor McClelland says, "Though we're using squeezing technology to reduce this too."

In optical astronomy replacing human eyes with sensitive photographic or CCD detectors enabled the same telescopes to achieve millions of times better sensitivity. Squeezed light detectors may do the same thing for our existing gravitational wave observatories.

Meta is better

Creating "impossible" optical materials

Lenses in one form or another have been used by humans since antiquity for magnifying small objects, lighting fires and even correcting defects in human vision. Since the day a Dutch spectacle maker discovered that two suitable lenses could form a telescope; the science of optics has gone from strength to strength. Today for the same price as a bag of groceries, one can purchase a sophisticated multi element camera lens that is truly a masterpiece of optical engineering.

In spite of all the progress, there are limitations too. All of the different types of glass available to optical engineers today have, for the most part, broadly similar optical properties. So there's only so much you can do with them.

To a large extent this is dictated by what nature gives us to work with. A glass is composed of atoms with charged nuclei and negative electrons sharing orbitals with their neighbours. Light is an oscillating electromagnetic wave. So when it enters this charged environment complex interactions occur between its own electric and magnetic fields and that of the lattice atoms. Seen from a distance this interaction has the effect of bending the beam.

Given this mechanism of operation, it's fairly clear that glasses with different atoms and different electron configurations will bend the beam in slightly different ways – a property known as refractive index. But in general all atoms and all glasses tend to behave in fairly similar ways. And because we only have a hundred or so elements to chose from there are limits to what can be achieved.

However in recent years, scientists have been developing ways to cheat. Rather than simply making optical materials out of homogeneous blends of atoms, it's possible to create little clumps of atoms and alternate them to make an artificial lattice. These so called metamaterials can be engineered to have properties that would be totally impossible to achieve with conventional compounds.

Fabrication of such materials for visible wavelengths is technically extremely difficult but with microwaves, which of course have the exact same physics, it's becoming a hot area of research.

Dr Ilya Shadrivov leads a group at the Australian National University developing metamaterial optics for microwave applications. "In the past we've created materials with negative refraction and other exotic properties," He says, "But these have all been fixed architectures."

The microwave metamaterials are fabricated in a similar way to a printed circuit board with a lattice of carefully engineered copper tracks that interact with the passing microwaves in just the same way the atoms of a glass interact with light. But to date, even though these new microwave metamaterials have exotic properties, those properties have been fixed. This means that a microwave lens or mirror made in this way can only behave in one way.

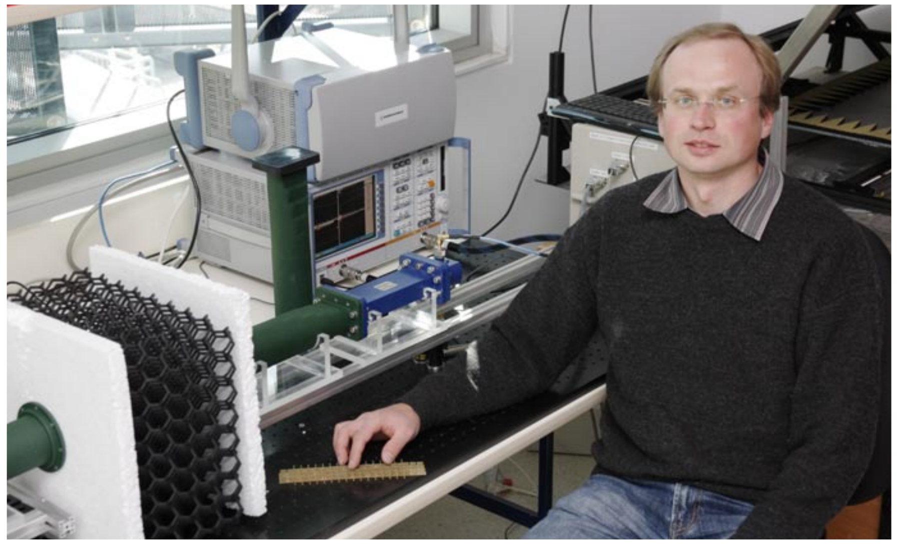
"It occurred to us that if instead of building the lattice using simple tracks, we used electronic circuitry including light-sensitive photo-diodes, then we could control the refractive properties at will." Dr Shadrivov says, "On the prototype I was changing the direction of the microwave beam simply by lighting the metamaterial with the torch on my phone which was really cool!"

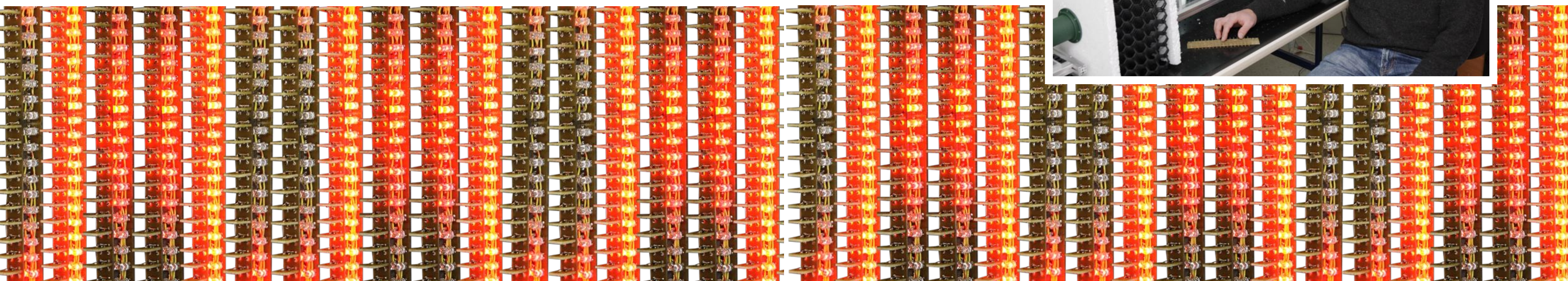
The group and their collaborators are now producing matamaterials in which each "meta-atom" element has its own LED illumination. This enables them to not only vary the properties of the material but to do so differently in different regions.

The technology can potentially have applications in radar and communications. "Using materials like this we can create a satellite dish that isn't a dish at all, it's a flat disc. And we can change properties like its focal length and reflectivity without changing its physical shape at all."

Radar and communication dishes that reflect, refract or simply disappear under optical command offer the possibility of exciting new devices for both military and civilian applications.

Right: Dr Ilya Shadrivov with a fixed microwave meta material. Below: The prototype light programmable material





A speckle of matter

Final confirmation of the matter laser

Have you ever noticed that when you look at the spot of a laser beam on a piece of paper the halo around it has a fine speckle pattern? The reason for this is that the laser light is coherent, that is each photon in it is identical to the others in wavelength and phase. What this means is that when the light hits a rough surface like paper the microscopic peaks and valleys in the surface each scatter the light in different directions. They act as independent sources of coherent light, and the result is a strong interference pattern which we see as speckle. However, the phenomenon of speckle isn't just confined to light.

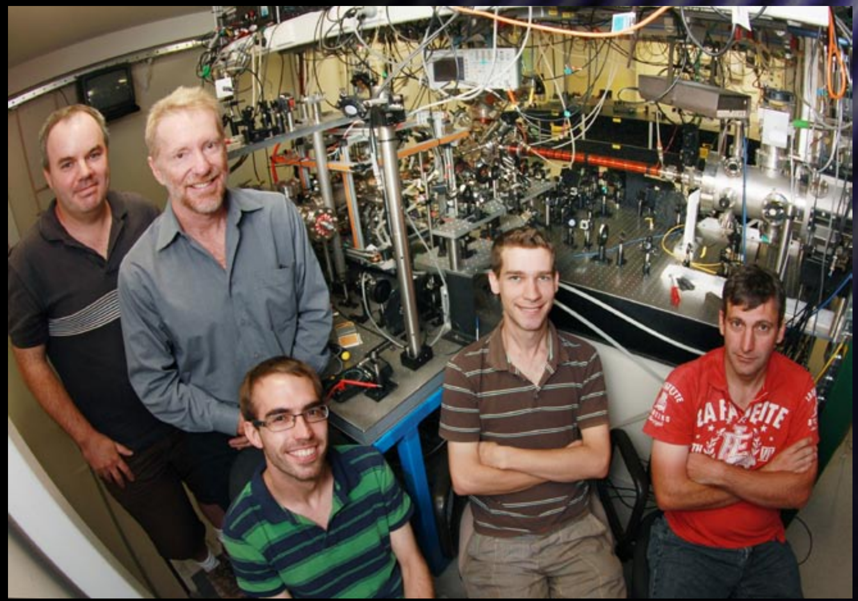
One of the great physics discoveries of the twentieth century was de Broglie (or matter) waves in which a stream of particles such as electrons, atoms or even cannon balls, also exhibit wave-like behaviour. In this way electrons passing through an aperture are diffracted in just the same way as light or ripples on water would be. In a stream of atoms created at room temperature, the atom velocities and times of release all vary. This in turn causes their de Broglie wavelengths and phases to all be different.

However, another of the great discoveries in modern physics was that of the Bose Einstein condensate, or BEC. This is a strange form of matter in which a collection of atoms are made so cold (within a millionth of a degree above absolute zero) that they all settle down into a single quantum state – something that would be completely impossible at normal temperatures.

In recent years scientists around the globe have been able to create BECs and then allow the atoms to leak out creating a beam of identical atom waves. Because they're all in the same quantum state, their de Broglie wavelengths and phases are all the same too, so in effect what you have is a laser beam made of matter rather than light.

Of course theoretically you'd expect that such an atom laser would generate the same speckle pattern as a light laser does. However, observing this in practice is a very difficult thing to do because each stage - the creation of the BEC, the creation of the atom laser beam and the creation and detection of the speckle pattern is incredibly difficult to achieve. However, a team of scientists at ANU have recently become the first to observe just such speckle from a beam of ultra-cold atoms.

"This is exactly the result we would have expected from theory," Professor Ken Baldwin says, "But we've gone even further to show that the coherence properties of matter wave speckle match those of light speckle. This enables us to use such properties to determine whether atom lasers are suitable for use in future devices, such as atom interferometers for gravity wave detection."



Some members of the scientific team, Dr Andrew Truscott, Professor Ken Baldwin, Andrew Manning, Sean Hodgman and Dr Robert Dall

Science & aerosols

Drs Steven Cavanagh and Stephen Gibson. No university buildings were injured in the making of this photo!

How advances in spectroscopy may change climate science

When you look at the spectrum of sunlight, you see a broad rainbow of colours over which are superimposed many fine dark bands. These correspond with the particular wavelengths of light that are absorbed when electrons transition from one energy level to another within the atoms and molecules of the sun's atmosphere. The fact that these lines are quite sharp is actually one of the easiest ways to verify that we do indeed live in a quantum universe, in which an atom's electrons are only allowed to occupy certain energy levels and not those in between.

Information gathered from this kind of spectroscopy has been of enormous importance in understanding both the fundamental structure of matter and how chemical reactions work at a nuts and bolts level. However, in spite of its usefulness, absorption spectroscopy does have its limitations. It's especially hard to do on very diffuse and lightly absorbing materials such as the low pressure gasses of relevance to atmospheric physics.

Since the late 1970s, scientists have also been using a slightly different approach to spectroscopy, illuminating a gas sample with a tuneable laser and studying the electrons that are liberated from atoms and molecules as the wavelength of the light is changed – so called photoelectron spectroscopy. This technique is particularly effective when used with negative ions where it's called photodetachment spectroscopy. In this case the extra electron becomes detached from the atom or molecule when the laser light hits, creating a neutral and a free electron. Because the behaviour of the electron is inherently linked to the atom or molecule it was originally sited on, measurements made on such an electron can yield information not only about the original ion but also the remaining neutral too.

One of the advantages of this technique is that it's sensitive. With conventional absorption spectroscopy if you hit a gas cell with a million photons and three are absorbed the change in intensity from 100% to 99.9997% is very hard to see. However, using photodetachment spectroscopy, the three resulting electrons are, with modern detectors, relatively easy to see.

Photodetachment spectroscopy is also great because whilst it enables you to see the same information as conventional absorption spectroscopy, it also probes additional electron transitions that can occur as these excited electrons fall between finely spaced upper energy levels in atoms and molecules – something completely invisible in a conventional absorption spectrum.

To extract all the information from such an interaction between light and matter, one would ideally like to know not only the number of electrons released when the laser hits, but also their energy and direction. Early photodetachment spectroscopy systems could only achieve that by essentially swinging the detector assembly around the sample. This was very time consuming and also could lead to contamination of the results caused by mechanical errors and residual electric and magnetic fields associated with the large metallic detector assembly physically moving about.

However, a team of scientists at the Australian National University have recently developed a photodetachment spectroscopy system that is by far the most sensitive, accurate and efficient in the world. The key to success was the design of a special electrostatic lens and detector assembly.

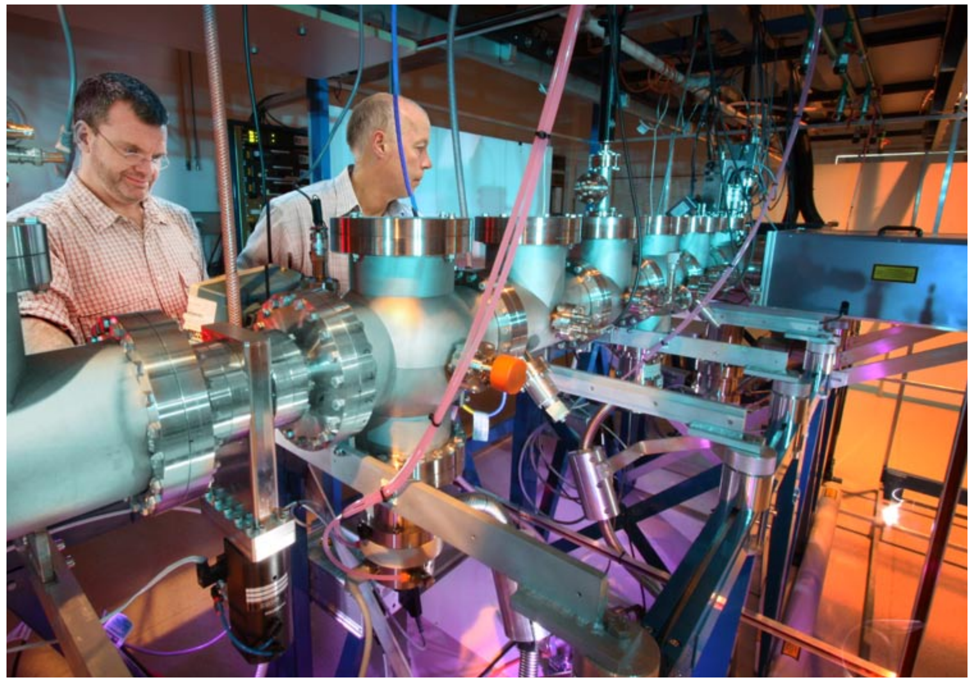
The electrostatic lens is a series of charged cylinders that produce an electric field with a smooth and accurate curvature. Electrons passing through this field are bent in the same way photons of light hitting a curved glass lens are brought to a focus. "Our system builds on the work of many others in the field," Dr Steve Cavanagh says, "Though we're really proud of the fact that at this point in time, ours is by far the most effective system of its kind in the world."

The ANU system is also innovative in that it requires no moving parts and unlike many early systems, does not require the gas/laser interaction zone to be microscopic. "We can allow the laser spot to reach a couple of millimetres without compromising our resolution," Dr Steve Gibson says, "and that's really important when you're dealing with low pressure gasses and very low concentrations of the species you're trying to study."

"What we're doing, particularly with modern aircraft, is injecting aerosols directly into the upper atmosphere"

But what is it that drives scientists to study the photodetachment process in the first place? "What we're looking at here is essentially the foundations of the chemical reaction process that drives everything." Dr Cavanagh explains, "In the process of a chemical reaction there's often a transitional phase between the reactants and end products, and that can last for as little as a femtosecond. Photodetachment spectroscopy is one of the only ways you can actually study this and if we understand this better, we understand all of chemistry better."

As with any new scientific tool, like a big new telescope, one of the decisions to make is where do you point it? What's the most important thing to study at this point in time? In the case of the ANU photodetachment spectrometer, one of the answers is atmospheric chemistry and it's effect on climate.



Drs Steven Cavanagh and Stephen Gibson with the ANU photofragment spectrometer

It's been known for some time that negative-ions play a pivotal role in the formation of aerosols within the upper atmosphere. These microscopic clusters of molecules can, depending on their nature, reflect or absorb solar radiation. They also serve as nucleation sites for water vapour droplets creating clouds, which of course also have the ability to reflect sunlight away from the Earth.

"Aerosols, play an enormous role in regulating the amount of solar radiation hitting the surface of the planet." Dr Gibson says. "And the formation, reaction and dissociation of these aerosols is turning out to be way more complicated than anyone had imagined. Unless you can really understand this process, you're totally in the dark when it comes to accurate climate modelling."

One compound of particular interest is sulphur trioxide SO_3. SO_3 and water combine to create sulphuric acid, the basis for acid rain. Volcanos and human activity, via industry and transport, inject vast amounts of SO_2 into the atmosphere which can further oxidise to produce SO_3 and of course there's no shortage of water up there. However, this reaction turns out to be not so straight-forward as was once thought. There is a potential barrier to overcome before a single SO_3 and H_2O molecule can combine. And over most of the Earth's atmosphere, there simply isn't enough free energy to overcome this barrier. However, in the presence of two water molecules, the barrier is lower and with three, lower still. "Given enough water molecules, the barrier effectively disappears. "Dr Cavanagh says, "So we see a very efficient conversion of Sulphur trioxide into sulphuric acid."

Apart from acid rain, these sulphuric acid molecules are important as they tend to form little clusters with other molecules such as water and ozone which form the basis of aerosols which can serve as nucleation sites for water droplets that will eventually build clouds.

"One of the things that this work has highlighted is the relative stability of negative ion species," Dr Cavanagh says "Compounds that would be hopelessly unstable as neutrals can often persist as negative ions for long enough for chemical reactions to take place."

This explains a relatively recent discovery that high concentrations of highly reactive sulphur compounds such as SO_3 have been found in the exhaust of jet engines when one would theoretically expect the extreme conditions to dissociate them. "What we think is happening is that the presence of negative ions is substantially increasing the lifetime and hence reactability of many of these compounds," Dr Cavanagh explains, "And that's quite worrying because if they're produced at ground level, they will mostly dissociate by the time they reach the upper atmosphere. But what we're doing, particularly with modern aircraft, is injecting them directly into the upper atmosphere at altitudes of 10 to 15 kilometres. If aerosols create clouds and clouds reflect sunlight it may not all be bad news, but in effect we're engineering our own atmosphere before we understand the science properly. And that's quite concerning given the consequences of humankind's latest efforts at atmospheric engineering with CO_2."

Connecting the dots

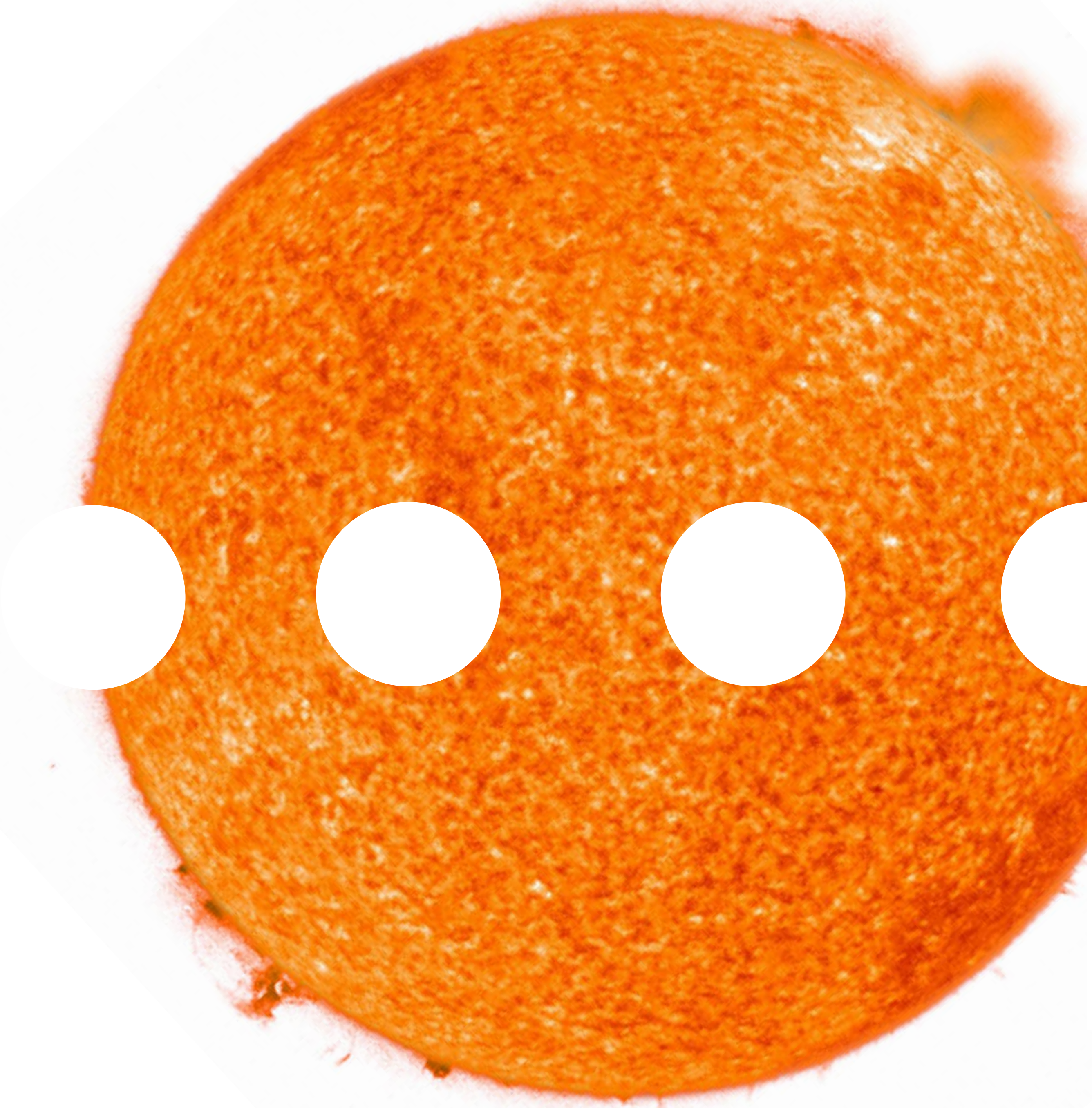
Metals such as copper are excellent conductors of electricity because they're full of highly mobile free electrons. Insulators such as glass on the other hand, have virtually no free electrons within their lattice so have little ability to conduct.

In-between lie the semiconductors like silicon. Semiconductors occupy a rather unique place in that although in their pure state they have few free electrons, these can be generated by light, heat or suitable chemical additions known as doping. A key feature of semiconductors is that they have an energy gap – a range of energies that electrons are not allowed to occupy.

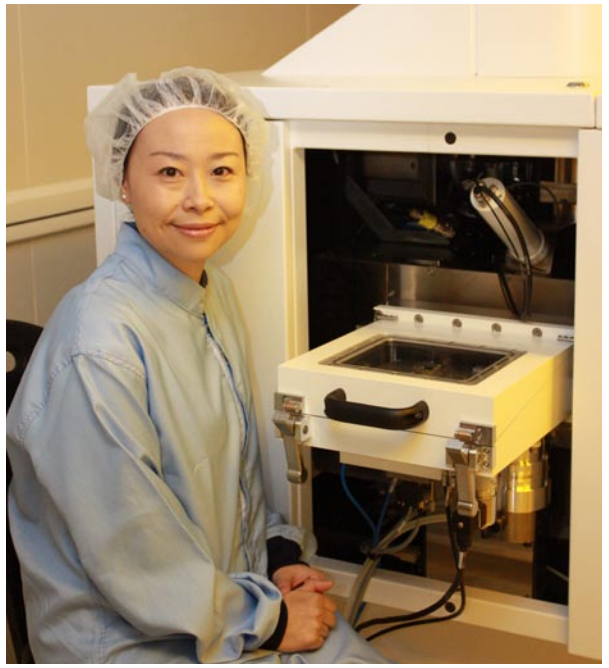
One increasingly important use of semiconductors is the creation of photovoltaic solar cells to convert sunlight directly into electricity. In such a cell the energy of photons of sunlight is used to separate an electron from one of the atoms in the crystal lattice, lift it over the energy gap enabling it to move freely and hence conduct electricity.

However in addition to this electron, there is a hole left behind in the sea of electrons surrounding the lattice atoms. These holes are also able to move – although of course what's really happening is successive electrons are filling the hole leaving another hole where they were. But the effect is that of a moving positively charged hole.

When it comes to making a solar cells from semiconductors, there are two major challenges. One is to extract as much energy out of the sunlight as possible so that ideally every single photon of light creates an electron-hole pair. The other is to get these electron-hole pairs to all migrate to the electrical contacts where they can do useful work rather than simply recombining somewhere in the middle of the cell.



"One of the challenges in this project is to design cells that harvest the full solar spectrum"



How nanotechnology could revolutionise solar power

A cell made of a single material like silicon is inherently limited because the band gap of silicon only enables it to absorb photons over a certain energy range. Now for say a domestic solar panel this may be fine, an efficiency of 10 or 20% may be acceptable. However in more critical applications such as a space craft or solar car where you really want the most power from the smallest lightest solar panel, it may not be good enough.

To make cells more efficient engineers have turned to other semiconductors like gallium arsenide and indium phosphide. These composite materials offer a wider variety of energy gaps that can be better tuned to sunlight. In addition by using a stack of two or more cells of different materials on top of each other, the one at the back can capture some of the photon wavelengths that the one at the front wasn't able to use.

Dr Lan Fu leads a group of scientists at the Australian National University looking at how complex compound semiconductors grown in microscopically thin stacks can create highly efficient cells. But the key to success here goes far beyond standard semiconductor materials and structures. More significantly, it will rely upon the group's strong background in nanotechnology and quantum engineering.

One technique they're employing is the use of quantum dots – tiny blobs of one semiconductor grown on the surface of another. They're so small electrons and holes trapped within them experience quantum effects. If correctly engineered, a sheet of quantum dots can behave very much like a conventional semiconductor however now the energy gap is dictated not only by the chemistry, but also the geometry of the materials. This means that custom bandgaps can be engineered that would be quite impossible using conventional technologies.

The plan is to create an advanced but conventional multi layer compound semiconductor solar cell then add an additional quantum dot layer to the back. This additional quantum layer has the potential to significantly increase the already high efficiency of the multi junctions above by capturing the infrared photons that elude the bulk materials above. Because the quantum dot technology is so flexible, it should in principle be possible to tailor the cells absorption to perfectly fit the sun's spectrum.

The initial research has been focused on the study of single junction QD solar cells and the results have been very encouraging, the response of the cells extending into the infrared well beyond the wavelengths that can be utilised by conventional cells. The electric current that's available from a solar cell is dictated by the number of photons of light it absorbs and the efficiency with which the carriers migrate to the contacts without recombining within the cell. On all those points the prototype scores well.

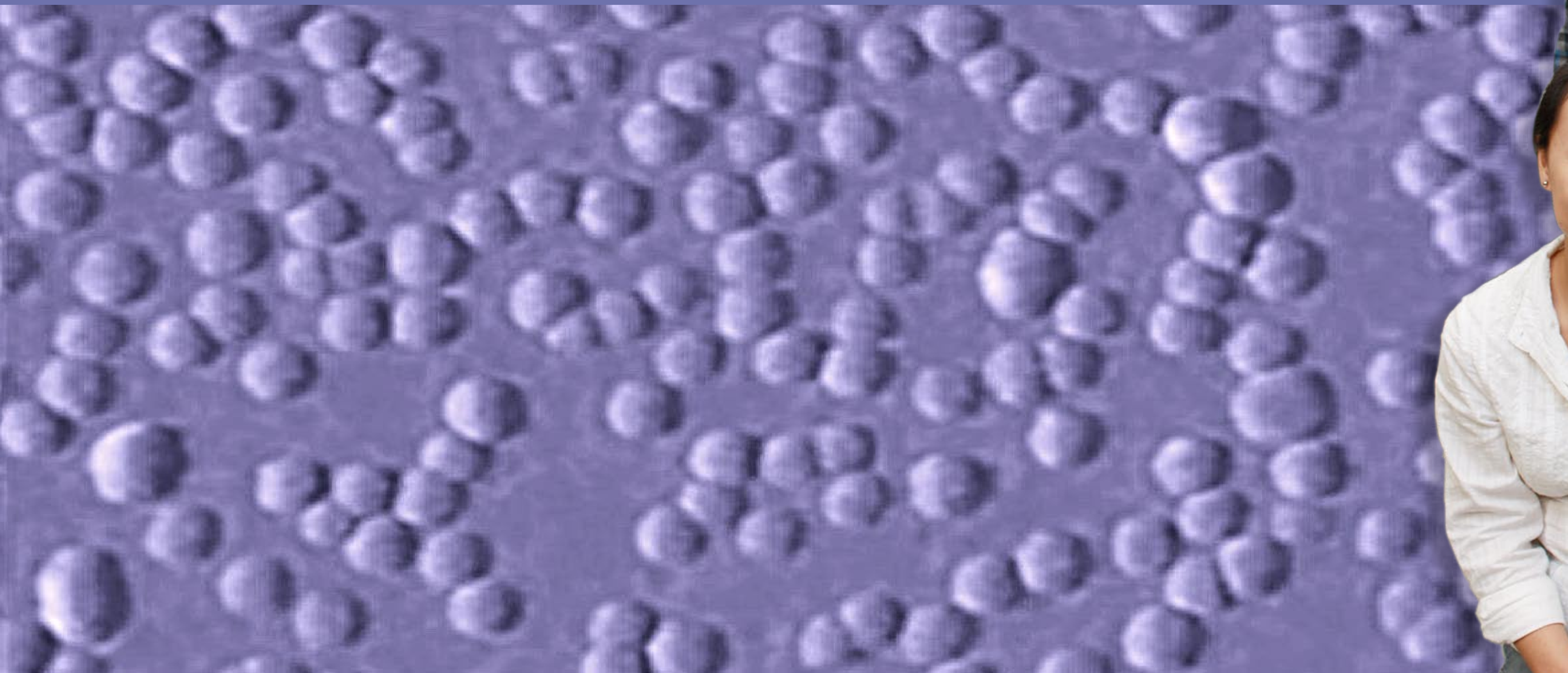
However the greatest challenge facing QD solar cells is controlling the impact that the QD structure has on the cell voltage. The quantum effect in QDs has some influence on this since it makes the electrons and holes recombine more easily as they travel through the device. Because power equates to voltage multiplied by current, this offsets some of the additional efficiency gained.

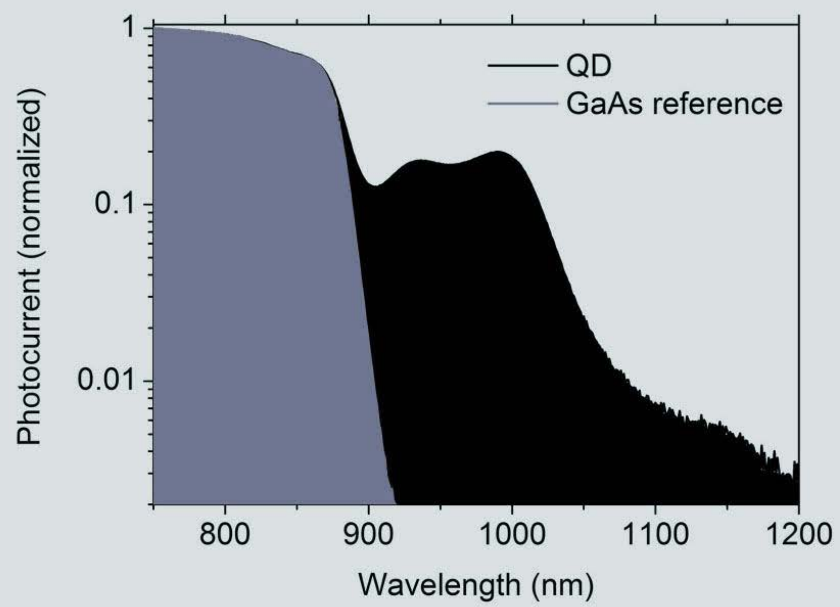
"One of the challenges in this project is to design cells that can be used in multiple layers to harvest the full solar spectrum, yet to configure those devices such that we don't compromise the Voltage generated." Dr Fu says.

At this point in time the primary interest in such super high tech cells is specialist applications such as space craft. However, as with all technologies, refinement and volume production brings the costs down and down. Thirty years ago it would have been totally inconceivable to have a microprocessor in your vacuum cleaner or car, yet now it's common.

If cells of even 50% efficiency can be cheaply created, the average house could be self sufficient for power with a panel no bigger than a table cloth on the roof. And a self charging electric car that runs for free and doesn't pollute becomes a very real possibility. Perhaps in the future you'll pay more to park on the sunny roof of a multi-storey car park rather than less!

Atomic force microscope image of quantum dots on the surface of a semiconductor





Left: The quantum dot layer gives the new solar cell a hugely improved response in the infrared

Below members of the team, Dr Fu lan, Dr Greg Jolley and Haofeng Lu

Tractor-beam one step closer to reality

New optical vortex pipeline transports matter

Drs Yana Izdebskaya, and Vladlen Shvedov make adjustments to a vertical version of the vortex transporter

If you put your hand into a shaft of sunlight, you can easily feel its warming effect and anyone who's been foolish enough to put their finger into a powerful laser beam will be very aware of how much heat electromagnetic radiation can generate. Such radiative heating not only warms any object in the light path, it also warms any gas, such as air, that's in contact with that object. The air molecules move a little faster when warmed and the increased force of their impacts with the surface of the object imparts a tiny thrust to it. This is known as photophoretic force.

It's a tiny force that you could never hope to feel on something as massive as your hand, but if the object is light enough, it can have a very noticeable effect. The famous Crooke's radiometer, a partially evacuated glass vessel with alternate silver and black vanes, operates on just this principle. When sunlight strikes the blackened sides of the vanes the air is heated slightly compared to the silver opposite side and the differential force makes the vanes spin round.

Although this phenomena has been known for over a century, it has recently found a new application in the world of nanotechnology. A group of scientists at the Australian National University have developed a system for the manipulation of small particles in air using a sophisticated optical vortex.

As its name suggests, an optical vortex is a beam of light that propagates as a very fast and tight spiral about a central axis. One of the properties of such vortices is that in the centre, the beams destructively interfere creating a dark core. If you were to project such a beam onto a piece of paper, you would see a ring of light with a dark centre.

If a very small particle is trapped in this dark core, interesting things begin to happen. As gravity, air currents and random motions of air molecules around the particle push it out of centre, one side becomes illuminated by the laser whilst the other lies in darkness. This creates a small photophoretic force that effectively pushes the particle back into the darkened core. The net result is that any particle in the vortex is pushed towards the core. In addition to the trapping effect, a portion of the energy from the beam and the resulting photophoretic force, pushes the particle along the hollow laser pipe.

If you replace the single vortex with two that are concentric but propagate in opposite directions, it becomes possible to move the particle back and forth along the pipeline by adjusting the brightness of either vortex.

A Crooke's radiometer

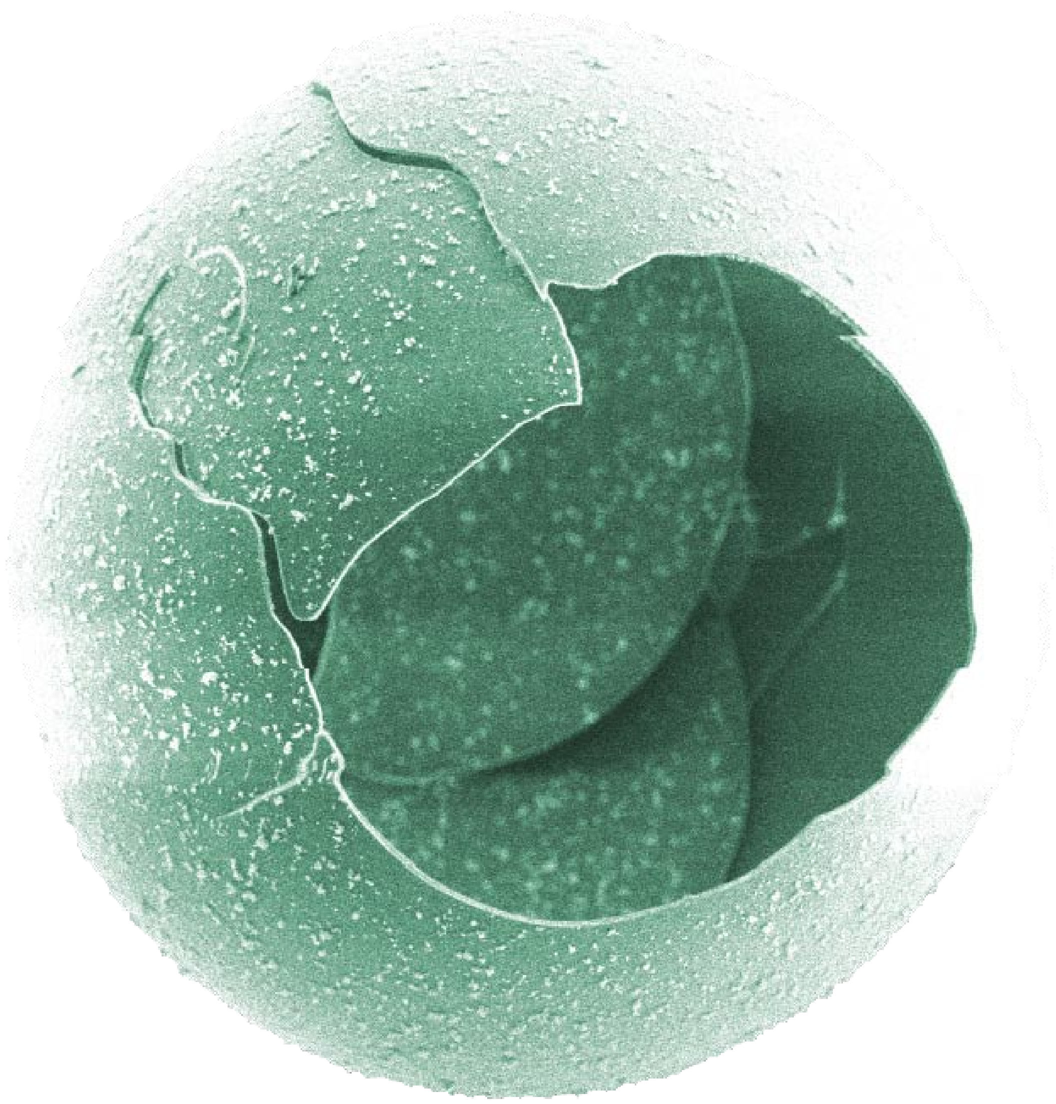
The choice of particle to move is also important to some extent though the system will manipulate almost any fine particle in almost any gas. "Ideally you want a surface that absorbs as much radiation as possible, like the black side of the vanes in a Crook's radiometer," Professor Andrei Rode explains, "You also need something light and with low thermal conductivity so the local heating stays local. We've done a lot of work in the past with carbon nanofoam, an agglomerate of carbon nano-particles. This material has excellent properties in all these areas, so it was our first choice when setting up the experiment."

The initial results were quite spectacular. The nanofoam particles remained securely trapped within the vortex whilst they were transported the full length of the optical bench. The system allows the manipulation of these particles with a few microns accuracy whilst being transported over distances of a meter or more. That's the same precision as being able to throw a rock from Sydney and land it in a skip in Canberra.

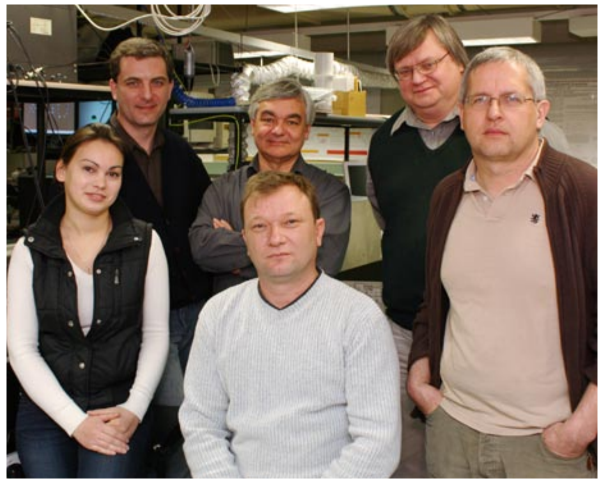
Although the nanofoam performed extremely well, working with alternative particles widens the potential applications and has other scientific benefits.

“The physical properties of nanofoam are ideal for this experiment but because it is irregularly shaped, it makes development of a good theoretical model quite difficult.” Professor Rode says, “And we really need an exact mathematical treatment of this process if we’re going to unlock its full potential.”

To achieve this, the researchers decided to use another type of particle, a tiny hollow glass sphere about one tenth of a millimetre across. However because the technique relies on absorption of laser light and local heating of the air around the particle, to work really well, the transparent glass had to be first coated with a thin layer of graphite.



The mass of the tiny glass spheres is calculated by breaking them and measuring the wall thickness with an electron microscope



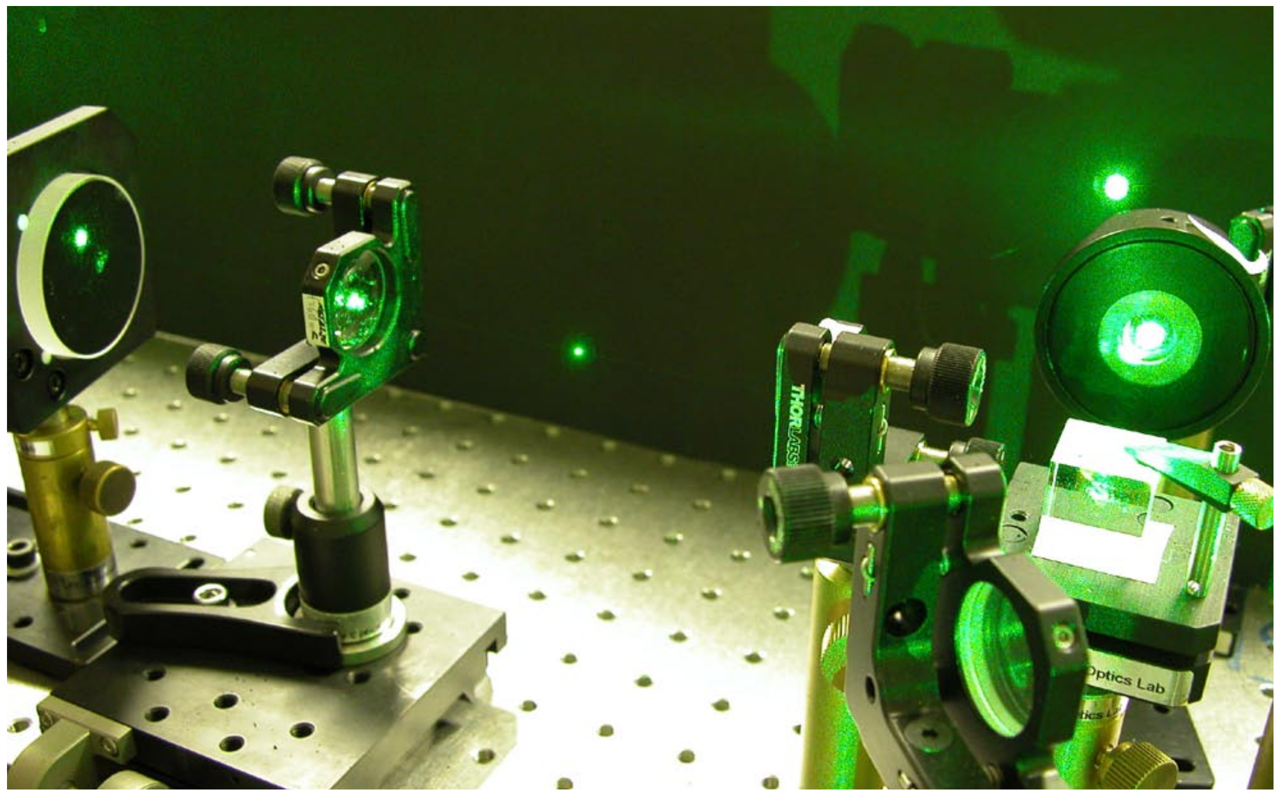
Members of the scientific team: Yana Izdebskaya, Anton Desyatnikov, Vladlen Shvedov, Andrei Rode, Yuri Kivshar and Wieslaw Krolikowski

The size of the coated glass shell can be relatively easily measured using an electron microscope but working out its mass is a little more complicated as there are no effective balances for measuring the weight of things this small. So having completed a series of measurements on a given particle, the researchers broke it and measured the wall thickness again with an electron microscope. From this they were able to calculate the volume of glass and hence the mass.

There are a number of practical applications for this technology such as micro manipulation of objects, sampling of atmospheric aerosols, and low contamination non touch handling of samples. But Professor Rode believes it’s hard to predict all the potential applications for any new technology. He tells a story about the Lebedev Physics Institute of the Russian Academy of Sciences, where he completed his PhD.

“There was a framed page from a PhD thesis in the library at Lebedev Physical Institute in Moscow, that of Nikoly Basov. Basov’s thesis was on a very early form of laser and a very eminent scientist, Giuzburd who was one of the examiners had written, ‘This work is very interesting but I see no practical application for it.’ Of course everyone knows how important lasers are today and Basov ultimately received the Nobel prize for his work, but this shows how difficult it can be to envisage what any new technology will bring to the world.”

This work is supported by a grant from the National Health and Medical Research Council



A microscopic glass sphere trapped in the dark core of an optical vortex

A singular problem

Mathematics in the search for the origins of the universe

When astronomers were first able to measure the velocities of stars and galaxies relative to the Earth, they noticed a strange thing. Almost all of them were moving away from us and the further they were from us, the faster they receded. You might be tempted to think that this is because the Earth lies at some special central point in the universe, but in reality it doesn't. The universe is expanding everywhere and an observer at any point would see the exact same thing. The same is true when you look at the distribution of stars and galaxies and the distribution of the cosmic microwave background left over from the big bang. Aside from local structure, the universe looks remarkably similar in all directions. This is a property scientists call isotropy.

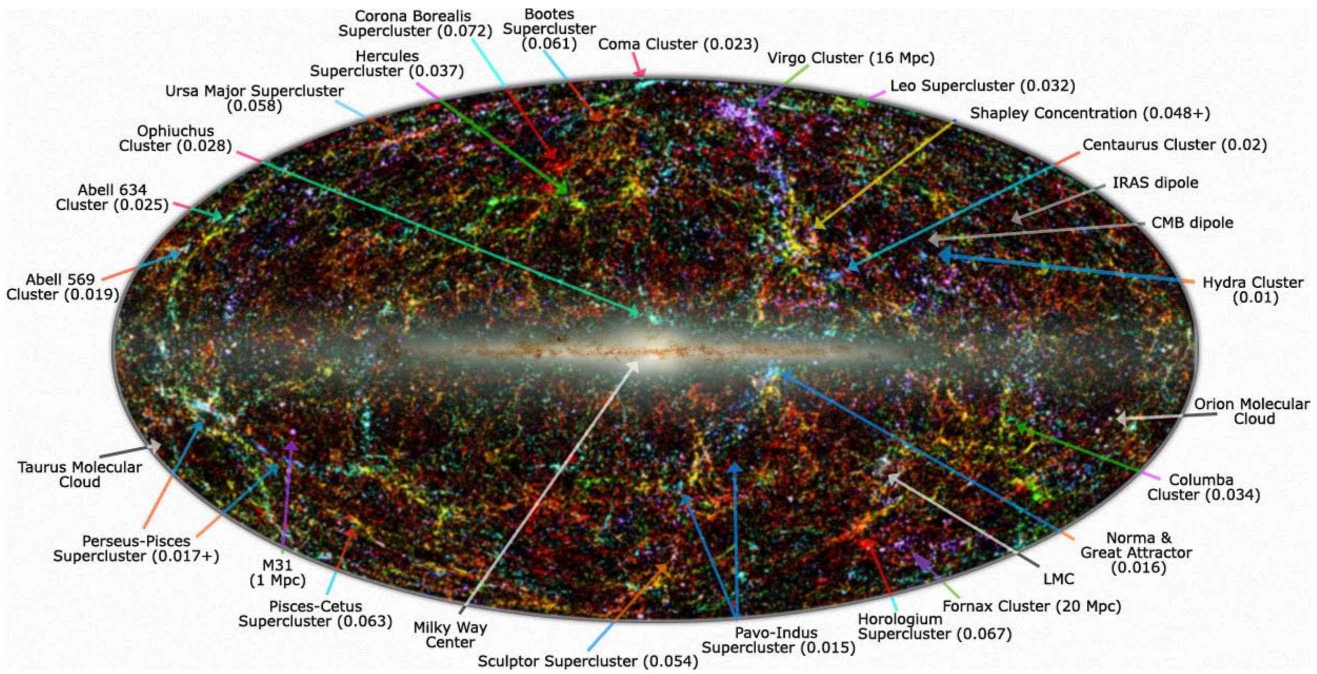
Why this should be so is one of the most intriguing questions in cosmology and a topic of great interest to Professor Susan Scott of The Australian National University. "There's really nothing special about where the Earth happens to be," Professor Scott explains, "so why we have this apparent isotropy is a really fascinating question. To answer it we have to better understand how the universe has evolved to the present time."

Unravelling that puzzle is the job of cosmologists. Because light travels at a finite speed, when we look at distant objects we are essentially looking into the past. This is a major reason why astronomers are always looking for larger and more powerful telescopes; distant galaxies are very faint, but the further away they are, the closer to the beginning of the universe we see them. And of course looking at how galaxies formed over time helps us to understand the formation of the universe in general.

However observational astronomy alone, can't solve the big questions of cosmology. To do that requires highly complex mathematical models into which scientists can plug data from astronomical observation and particle physics. There are a number of competing cosmological models but they all incorporate the idea of a big bang: a point at which the universe rapidly expanded from an infinitesimally small singularity.

A simple example of a mathematical singularity is f(x) = 1/x. When x = 0 the function becomes one divided by zero which is an undefined quantity. Although the mathematics of cosmology is far more complex, the essential problem is the same.

"Solving the mathematics of the big bang as well as the final state of the universe is complicated by the initial and possibly final singularities." Professor Scott explains, "You can't do much when things go singular."



The distribution of galaxies shows remarkable isotropy. Image: IPAC/Caltech, Thomas Jarrett

Professor Scott

To get around this, Professor Scott and her collaborators have been working on nice regular cosmologies that don't have singularities. Although these don't directly represent the physical universe we live in, they can be designed to have what's known as conformal relationships with the physical universe. What this means is that you can solve the maths in one universe and extract results that are meaningful in another.

"An early contender for modelling the universe was Chaotic Cosmology." Professor Scott says, "This is a theory in which the universe began with a big bang and entered an exceedingly hot and highly chaotic phase before organising itself in the way we now see. The problem is that whilst this is a nice picture, it's not really compatible with either observation or thermodynamics which requires that entropy increases with time."

The more recent Quiescent cosmological model still incorporates the notion of a big bang but the key idea is that the gravitational field also has an entropy associated with it. So in effect you have an early universe in which the gravitational field is very smooth and has very low entropy whilst the first matter to condense had a very high entropy. As time progresses the situation slowly reverses, with the gravitational field increasing in entropy as the matter cools. Of course the combined overall entropy has to increase in accordance with thermodynamics.

"Our work enables us to solve some difficult problems in the Quiescent cosmological model." Professor Scott says, "A while back we had been able to incorporate the initial singularity of the big bang. Now we've recently expanded that work to model the final singularity that might be seen in a big crunch scenario, where the matter of the universe contracts back under gravity to a single point again. However this work isn't about predicting whether the universe will continue to expand or collapse into a big crunch. The maths works equally well for both scenarios so we have to leave it to the observational cosmologists to provide some numbers to plug in."

The most recent observational work suggests that the expansion of the universe, far from slowing down with time as one might expect in a big crunch scenario, is in fact accelerating. Astronomers have dubbed this phenomenon dark energy in reference to the unknown force that may be causing it and it's a hot topic in modern astronomy.

"I think there are three really big unsolved questions in physics at the moment." Professor Scott says, "The nature of dark energy, the unification of fundamental forces and of course us, by which I mean are we unique in the universe or not?"

It may be some time before we're able to answer any of those questions but it's certain that when we do, mathematics will play a central role.

Nanobubbles

The last word in cleaning?

When we wash our dishes, we're removing protein, fats and all manner of other contaminants from a ceramic surface. If you were to simply run cold water over the plates it's unlikely that the results would be very satisfactory. However a combination of what's known as a surfactant (soap), warm water and a bit of scrubbing with a sponge achieves what most householders would call a nice clean plate. But just how clean is such a surface at the molecular level? Probably not very! There are many proteins that bond extremely well to surfaces leaving a layer perhaps only a molecule or two thick - fine for hygienic dining, but not good enough for some scientific and industrial applications.

Many industrial processes require components to be so clean that their surfaces have no trace of contaminants. To make matters worse some components such as the metallic parts of silicon chips or detectors can't be scrubbed or abraded in any way. This can necessitate the use of multistage cleaning processes that can be messy and expensive. However a group of scientists at the Australian National University have recently discovered a simple technique that may have widespread potential to revolutionise a whole range of industrial and domestic cleaning applications. The secret is nanobubbles.

When an electric current is passed through water, electrolytic decomposition of the water molecules results in the production of oxygen and hydrogen gas. The process occurs rapidly in salt water but very much more slowly in pure water because of its vastly lower conductivity. This in turn is due to the fact that water has a very limited ability to self ionise, in other words for two H_2O molecules to become hydronium H_3O^+ and hydroxide OH^-.

The upshot of all of this is that when a small voltage is applied between a conductive component and a second electrode in a water bath, bubbles of gas begin to form. If the component is used as the cathode (negative electrode) hydrogen gas forms on its surface. But if the water is pure, the conductivity is very low and the quantity of gas is miniscule. This means the bubbles that form are only a few nanometres across – way too small to see even with a microscope.

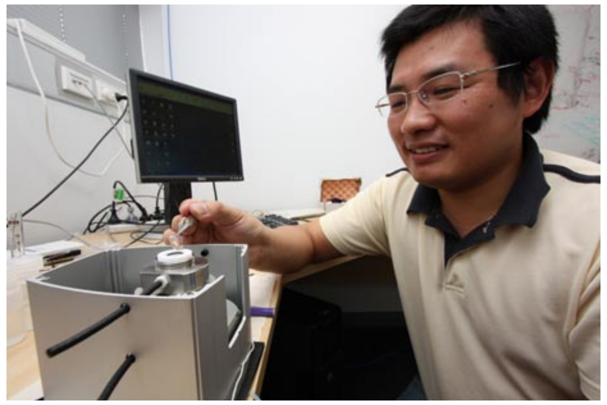
However, although the bubbles may be invisible, their effects are not. The gas forms directly on the surface, beneath the contaminants. As the bubble grows it lifts the surface film and carries it off into the water when the bubble leaves the surface. If the process is repeated a few times it is possible to clean a component in a matter of seconds without the use of chemicals or abrasion.

Nanobubbles are a relatively recent discovery; scientists hadn't looked for them because in theory, they shouldn't exist. When a bubble of gas in a liquid is very tiny, the quantity of gas it contains is miniscule and it's surface area is large. Its Laplace pressure (the pressure difference between inside and outside the bubble) is also very high. All this should lead to such tiny bubbles simply dissolving into the surrounding liquid. The researchers believe that reason this doesn't happen when the bubble is on a surface is that the contact angle of the bubble to the surface is very much lower than would be expected.

Although nanobubbles may have many future applications in cleaning, the potential of this technology isn't limited to just removing contaminants. It may have a role in preventing the adsorption of materials onto conductive surfaces in the first place. One potentially exciting use of such a system is marine anti-fouling.

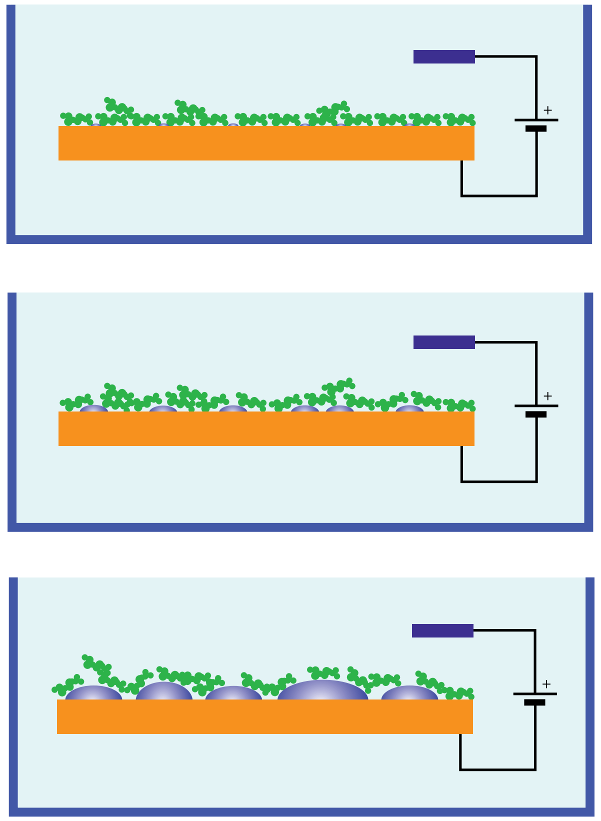
When ships are new their hulls are clean and smooth and they slide through the water easily and quickly. However, as they age, marine organisms such as barnacles begin to grow below the waterline creating a rough surface that induces turbulent flow and friction. To counter this, shipbuilders have used a number of techniques. One of the earliest was to attach copper sheets to the bottom of ships, leading to the common phrase "copper bottomed" – meaning solid and trustworthy. The use of copper bottomed ships with their higher speed was one of the deciding factors in the supremacy of the British Navy in the eighteenth century.

Modern ships are coated with toxic anti-fouling paint rather than copper sheets, but this is expensive and can lead to environmental problems when the paint needs to be removed and replaced. If one day it were possible to incorporate nanobubble technology into the design of ships, they may be able to clean themselves in the water without the need for toxic coatings.



Above: Dr Guangming Liu demonstrates the nanobubble cell in the lab. Nanobubble technology may be used to prevent organisms attaching to ships.

Below: Electrolytically formed nanobubbles on a conductive surface lift contaminants such as adhered proteins.



Signs of life

Applying nanotechnology to the search for extraterrestrial life

A century ago some astronomers believed that they could see colour changes in the Martian continents through their telescopes and speculated that this may be due to seasonal changes in vegetation. Back then, there were no space probes or orbiting telescopes far above the Earth's turbulent atmosphere, so this slender evidence was as advanced as the search for extraterrestrial life got. Of course, in the modern world we have sophisticated probes able to actually visit the surface of Mars and do some much more rigorous science. But how exactly do you look for life on another planet with robotic probes? Clearly if the images the probe sends back show little green men peering into the camera, you know you've found life. But what about the rather more realistic scenario of life existing in the form of bacteria or other microbes.

There are a number of ways to test for this using wet chemistry. Samples of soil can be mixed with water and nutrients and gas detectors can look for a tell tale "burp" indicating metabolism. The problem is that in spite of clever tricks like marking key molecules in the nutrient with radioactive isotopes it's very hard to eliminate the possibility of an unknown "dead" chemical reaction mimicking the effects of living organisms.

Another method that may side step this problem centres on a compound known as Dipicolinic Acid or DPA. DPA is a key component in the spores of bacteria and fungi and is often used as an indicator of life. Almost all cells on Earth contain DPA, so given that the rest of the solar system formed from the same basic ingredients, it would be a fair bet that extraterrestrial life would have evolved this way too.

One of the simplest ways to detect DPA is by its interaction with Terbium. Under UV light DPA becomes photo excited and then in turn excites any neighbouring terbium atoms by electron transfer. The up shot of this is that if you pulse terbium with UV it will give a characteristically different fluorescence when DPA is also present.

In order to test a sample of Martian soil for life, it could be dissolved in solvent then deposited on a terbium surface. Once the solvent had evaporated the fluorescence signature could in principle tell you whether DPA was present in the residue. One problem with this technique is that the signal is likely to be quite weak, especially if the quantity of spores or cellular debris in the residue is small.

Simply smearing samples over a flat terbium surface isn't a particularly efficient way to perform this test, since only the molecules on the very surface are in direct contact with the terbium and so are the only ones to be able to participate in electron transfer. One improvement would be to vastly increase the surface area of the terbium by making the surface highly convoluted. And one of the most convoluted and high surface to volume structures in existence is what's known as nanowool.

Nanowool is a material developed by a team of scientists at ANU lead by Professor Rob Elliman. It's a series of incredibly long silicon dioxide nano-filaments that grow into an interwoven mat on the surface of a silicon wafer when exposed to particular temperatures and atmospheres. In spite of only being a few nanometres across the huge length of these fibres and their large number create a mat that's easy to see and handle. When peeled off the wafer it looks like a little square of blotting paper. This provides the extraordinary surface area needed for interaction with DPA but to work as a detector, the system also needs terbium.

To achieve this, a solution containing terbium can be added to the nanowool mat and by capillary action will instantly cover the exterior of all the fibres. The matt can then be heated to boil off the solvents and anneal the terbium onto the outside of each fibre like the cladding on an electrical cable. This process can be repeated a number of times to either increase the thickness of the coating or even create stripes of different materials as desired.

You now have a sensor that by virtue of it's enormous surface area, is capable of identifying the smallest traces of DPA. It also has another potential advantage over wet chemistry. Once a measurement has been made it is possible to heat the detector to high temperature to burn off the residue and refresh the sensing capabilities. Since the nanowool is formed at high temperatures, it's relatively immune to heating damage.

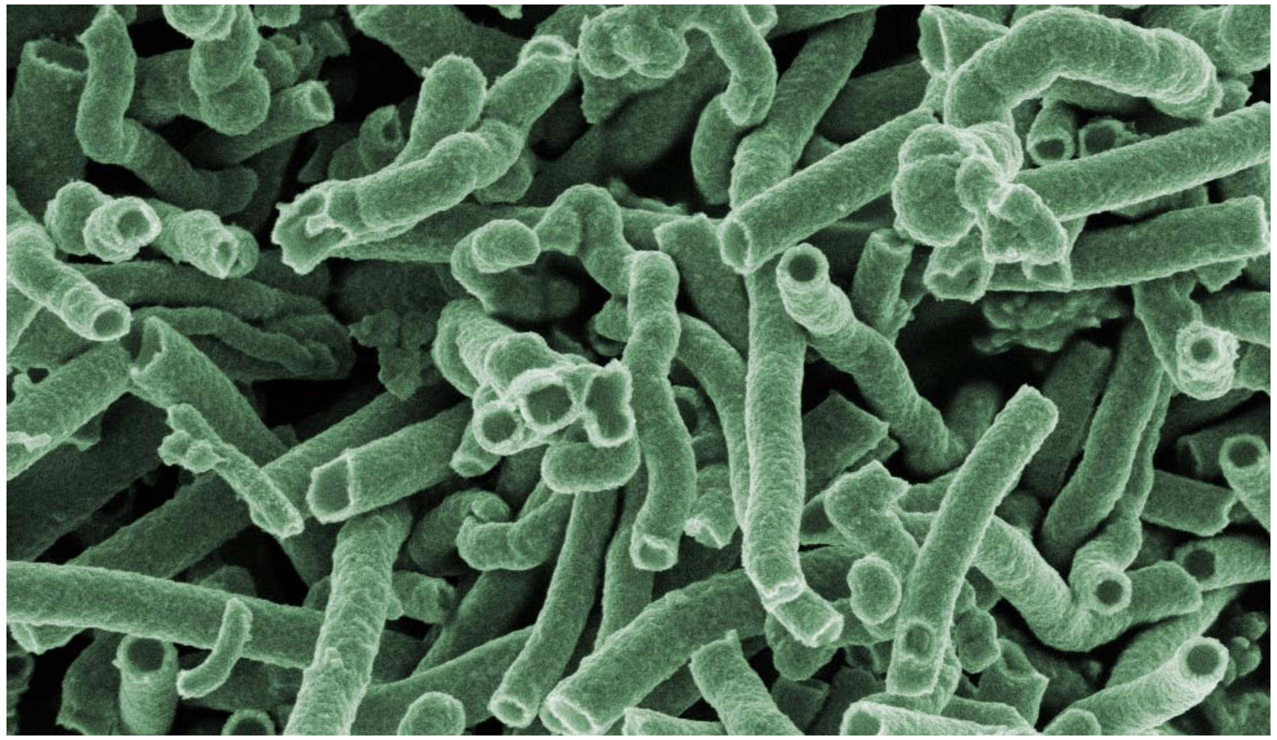
This feature may be of particular value on remote space exploration vehicles where it may be desirable to perform hundreds of tests using the minimum possible in-flight weight and space.

But the potential of nanowool DPA sensing isn't limited to space exploration. Back on Earth security forces are frequently confronted with situations where unidentified and potentially bio-hazardous substances are found in public places. Quick decisions have to be made as to the best course of action. If you do nothing you risk spreading a potentially deadly infection to the wider population but you can't quarantine hundreds of people somewhere like a shopping mall for the several hours or even days it takes for a full lab analysis.

In answer to this problem, several companies make on the spot detection kits for pathogens such as anthrax. One of the problems with current detection kits is that their sensitivity in certain areas is limited and they are single use only. Fluorescence based nanowool detectors may offer superior performance in this role and be able to provide more quantitative information about the nature of spores present in a sample and their concentration.

Above: Professor Rob Elliman, Dr Avi Shalav and Tae Hyun Kim in one of the fabrication labs at ANU

Below: False colour electron microscope image of TiO_2 coated nanowool



The light fantastic

When white light lasers meet photonic devices

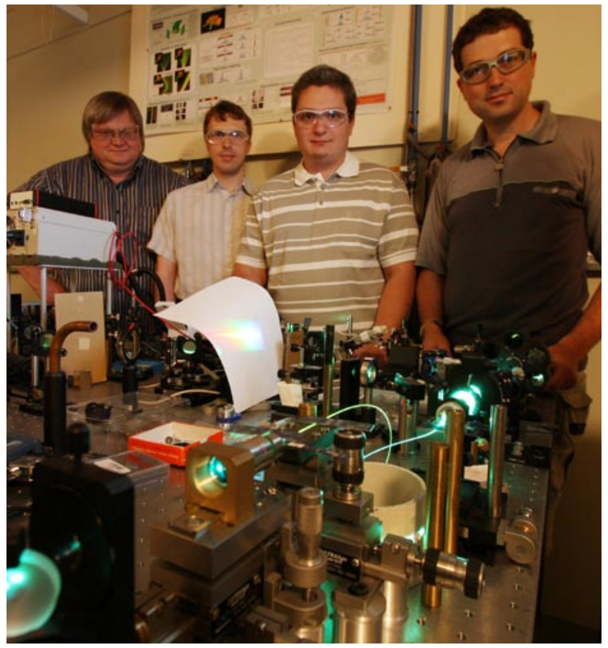
When we think of lasers, we usually imagine a narrow beam of light of a very particular colour such as that from a laser pointer - which is red, green or perhaps yellow. This single colour characteristic comes from the underlying physics of lasers. Within a laser, each photon is created as an exact replica of the others, so they all have the same wavelength and direction. This is one of the properties that make lasers so useful in a range of applications. But in some ways, it's also a hindrance.

Almost as soon as lasers were invented, scientists began investigating the possibility of broadening out the very narrow wavelength range. At first this amounted to little more than a slight smearing of the spectral peak. But during the last decade with the advent of advanced nonlinear optical materials and nano engineered optical fibres, lasers have been wavelength broadened to the extent that the light that comes out really does appear white. Scientists refer to such laser generated white light as a supercontinium.

One area in which supercontinium light promises great advances is in integrated photonic devices. These are essentially the optical equivalent of conventional electronic chips, such as a computer CPU. But optical chips have the potential to operate very much faster than their electronic equivalents in many applications.

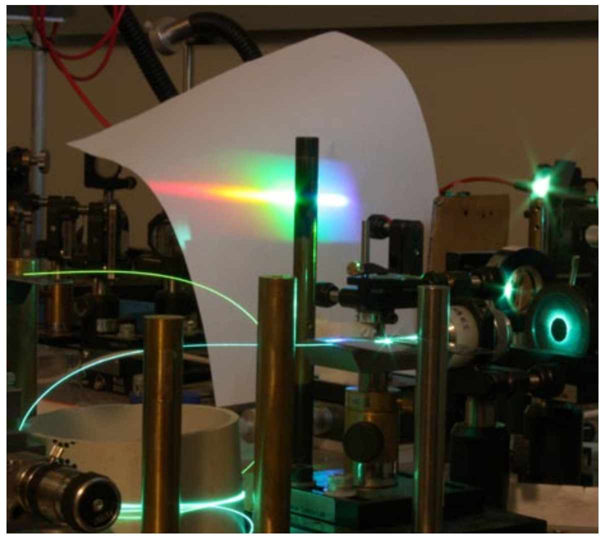
If one were able to run photonic chips using the white light of a supercontinium, there would be the exciting possibility of revolutionising numerous fields which require use of many different wavelengths at the same time, such as optical sensing and characterization, spectroscopy, tomography, metrology, and telecommunications. But before it's possible to unlock this potential, it's necessary to overcome the fundamental tendency of different colours to propagate quite differently in physical media due to the effects of dispersion and diffraction.

Dispersion is the tendency of materials to have different refractive indices for different wavelengths – it's what causes white light to be split into a rainbow by water droplets or a glass prism. Diffraction is a property experienced by all waves, including light, whereby the wave is scattered at an aperture or when it encounters a structure that has a regular series of lines or dots.



Professor Yuri Kivshar, Dr. Andrey Sukhorukov, Dr. Ivan L. Garanovich and Dr. Dragomir N. Neshev with a supercontinium light source

Bright spectrum developed by supercontinium laser



Diffraction is dependent on wavelength so if a structure is created that has a series of ridges with the right spacing, the effect is to also split the light into a spectrum.

Although dispersion and diffraction are common terms in optics, these phenomena are not exclusive to light. Wave particle duality tells us that electrons moving in a silicon chip are also in effect, tiny waves. These electron waves experience diffraction as they pass the regular rows of atoms in the crystal leading to a range of useful effects. In electronics, engineers use external applied voltages to control this movement of electrons and to some extent modify the effects of diffraction. What optical engineers would dearly love to do is something similar in optical chips. Unfortunately there isn't a simple equivalent of an applied external voltage for an optical chip, but a group of researchers have recently discovered a way to do something very similar.

Dr Ivan Garanovich works as a research scientist in the Nonlinear Physics Centre at ANU. He's part of a team investigating ways to simulate electric fields in optical chips. Their work centres on what are known as photonic lattices. These are regular arrays of lines created in transparent materials such as fused silica. The light waves interact with the lattice in the silica in a very similar way to electrons in the natural lattice of atoms in a semiconductor crystal. And this gives them the potential to make optical devices such as transistors and switches.

What the team have found is that if the regular lattice of the photonic device is bent into a gradual curve, the effect on the photons is almost exactly the same as that electrons experience when a voltage is applied to a semiconductor. If the curve is just in one direction, it's like a DC voltage. If the curve waves from side to side the effect is the same as AC.

"What we're really excited about is being able to use this technology to overcome diffraction and dispersion and synchronise the passage of different colours of light through the device," Dr Garanovich explains.

The microscopic photonic lattices are created by burning tiny grooves into a slab of polished quartz using a powerful laser on a computer controlled micromanipulation stage. Researchers then investigate the propagation of supercontinium light through these structures in various configurations and compare this with theory.

By calculating what the diffraction and dispersion effects will be within the photonic lattice and then introducing a curve to the structure, the researchers have been able to control the propagation of each wavelength. In the simplest case, this allows white light to propagate through the dispersive and diffractive lattice without splitting into component colours. But that's just the beginning of what's possible.

The important thing is that having an optical equivalent to voltage gives engineers an extra degree of freedom in designing components. This means that it's possible to utilize nonlinear effects at multiple wavelengths in the same medium. Using this technology, optical structures can be created that guide and process light in ways that far more closely mirror electronic devices. And that opens up a world of exciting possibilities.

Nanotechnology: A recipe for amazing devices

Nanotechnology is a hot topic in science at the moment, but what is it that's so special about making things very small? Nanoscale materials have a number of properties that make them behave in a fundamentally different way from the same material on a large scale.

Firstly, when a given quantity of material is broken up into pieces that are only a few nanometres across vastly more of the atoms lie on the surface than they would in a single lump with the same mass. This increases the surface area for reactions but it also changes the way the surface atoms are bonded. A combination of these effects makes many materials that would be inert in bulk behave in a very reactive manner when engineered into nanoparticles.

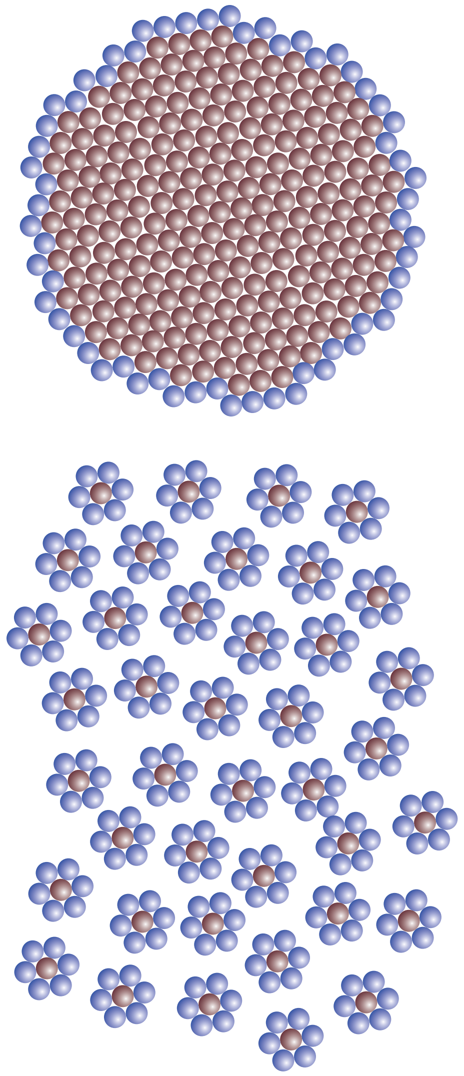
When semiconductor devices are created on the nano scale, these surface effects generate additional benefits. One of the performance limitations of devices like transistors and lasers is the presence of imperfections within the crystal lattice. These are simply a product of thermodynamics and are very difficult to totally eliminate in large-scale materials. However, when a structure is only a few atoms across the thermodynamics and internal stresses become quite different. It often takes more energy to create defects than to have a perfect lattice, leading to far better crystal growth. The small scale also means that you can stack materials that have different atomic spacing on top of each other in layers without the major disruptions to the lattice that would occur in large-scale structures, which is important in creating devices.

The second major change that happens as devices approach the nano scale is that quantum mechanics begins to play an increasingly important role in their behaviour.

By combining these nanoscale effects it has become possible to create semiconductor devices that would have been pure science fiction twenty years ago.

Professor Chennupati Jagadish leads a research group at the Australian National University focusing on the development of nano scale semiconductor devices.

"It's the combination of surface and quantum effects that make nanotechnology such a unique and interesting area to work in." Professor Jagadish says. "What we're doing is essentially engineering but at the atomic and molecular scale."



In nanoscale materials the ratio of the number of atoms on the surface to the number in the bulk becomes very much larger than it is in larger pieces of the same material. This vastly increases the surface area for reactions but it also changes the inherent reactivity of the material because surface atoms have fewer neighbours so the electron bonding is different.

One device Professor Jagadish's group are currently developing is a nanowire laser. These structures are just a few atoms across and are quantum engineered to achieve an amazingly efficient conversion of electricity into light. In the centre of each wire is a quantum dot – a region of material only a few atoms in each dimension. This incredibly small space only permits electrons to have very specific energies, defined by the quantum rules.

This in turn means that the light emitted is of very specific wavelengths. At either end of this central active region of the nanowire are multi layer reflective structures known as Bragg mirrors that complete the laser. One exciting application of nanowire lasers is in generating the single photons of light that are required for secure quantum communications.

But how do you create something like a nanowire laser in the first place? The answer lies with a technique known as Metal Organic Chemical Vapour Phase Deposition (MOCVD). Essentially, a stream of gas is passed over a heated semiconductor wafer known as the substrate. The gas contains organic molecules in complexes with the component atoms of the desired semiconductor. One of the most common semiconductors used is gallium arsenide (GaAs).

Nanowires rise from the surface of a semiconductor wafer. Image: Tim Burgess

The process begins with a super clean and highly polished GaAs substrate wafer being loaded into the reactor. The complex gases are then passed over the surface. At room temperature nothing much happens, but once the wafer is heated to about 600°C the gas begins to dissociate, depositing gallium and arsenic atoms on the surface of the wafer. The high temperature gives these atoms lots of kinetic energy to move around and the slow deposition rate allows them plenty of time to shuffle around until they create a perfect extension of the underlying lattice of the substrate wafer. In effect, the substrate wafer becomes thicker, but retains its perfect crystal structure. Of course if this were the end of the matter, it would be rather pointless because you'd just be making thicker wafers. But what the gas stream technique also allows you to do is change the composition of the additional material as it grows by changing the gas mix.

In this way you can build up layers with different compositions and different impurities giving each layer unique electrical and optical properties. The thickness of the layers in this sandwich can be controlled by the growth time, the longer you pass a particular gas combination over the substrate, the thicker that particular layer becomes.

At the end of the growth, you have a wafer that is typically 50mm in diameter with a multi layer sandwich on top. Because the wafer has perfect crystal structure, it can be easily cleaved along the atomic planes to create thousands of tiny individual devices each one of which is roughly 1mm square. But whilst that's fine for devices live DVD player lasers, it's still gigantic by nano engineering standards!

In order to create nano versions of these lasers you use the same basic method but there are a few extra tricks you need. Before loading the wafer in the reactor it has to be coated with a colloidal solution of ultra fine gold particles, each a few nanometres across. This creates millions of tiny dots on the surface of the wafer.

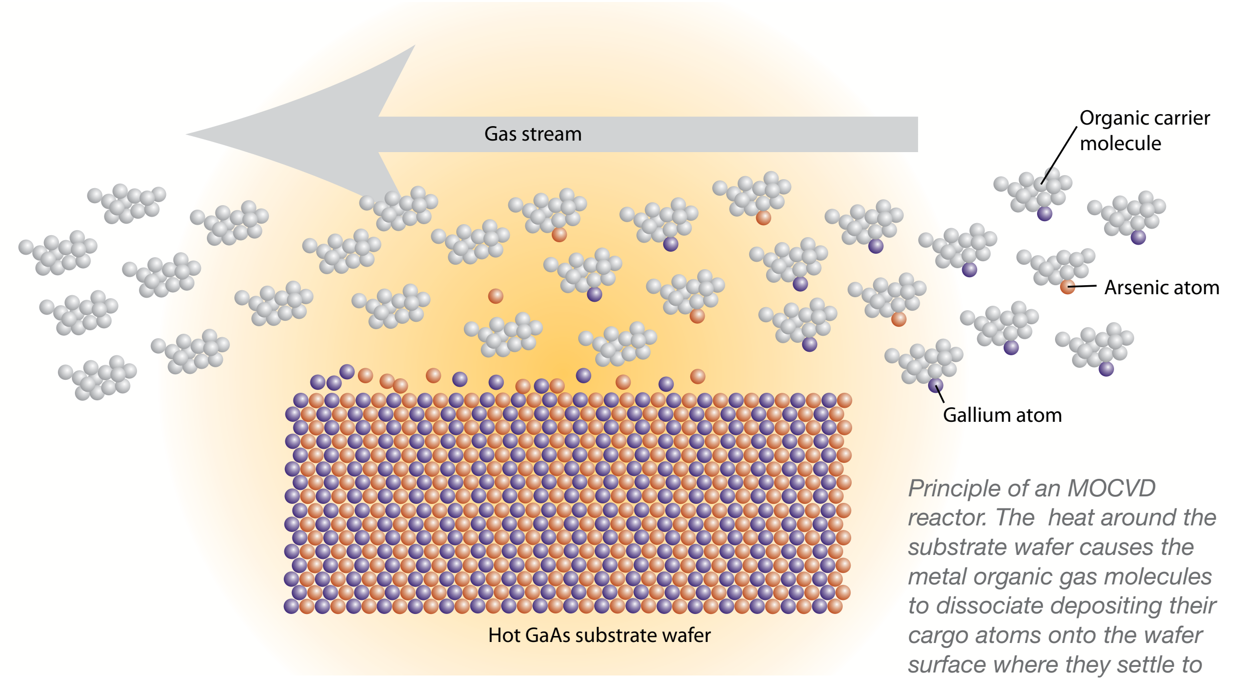
Gold itself has a very high melting point (1064°C) as does GaAs (1238°C) but when heated together, they form a eutectic – a compound with a very much lower melting point than its constituent parts.

If one were to heat the wafer to over 600°C as before and pass the gases over, an epitaxial surface layer of new crystal would form right across the surface and the gold eutectic wouldn't have much of a role. But if the temperature is kept down to around 400°C, the gases don't dissociate on the surface. However their metal cargo atoms do become incorporated into the liquid gold eutectic. This results in a super saturated solution of gallium, arsenic and whatever other compounds you have in the gas, forming in the nanoscale eutectic drop.

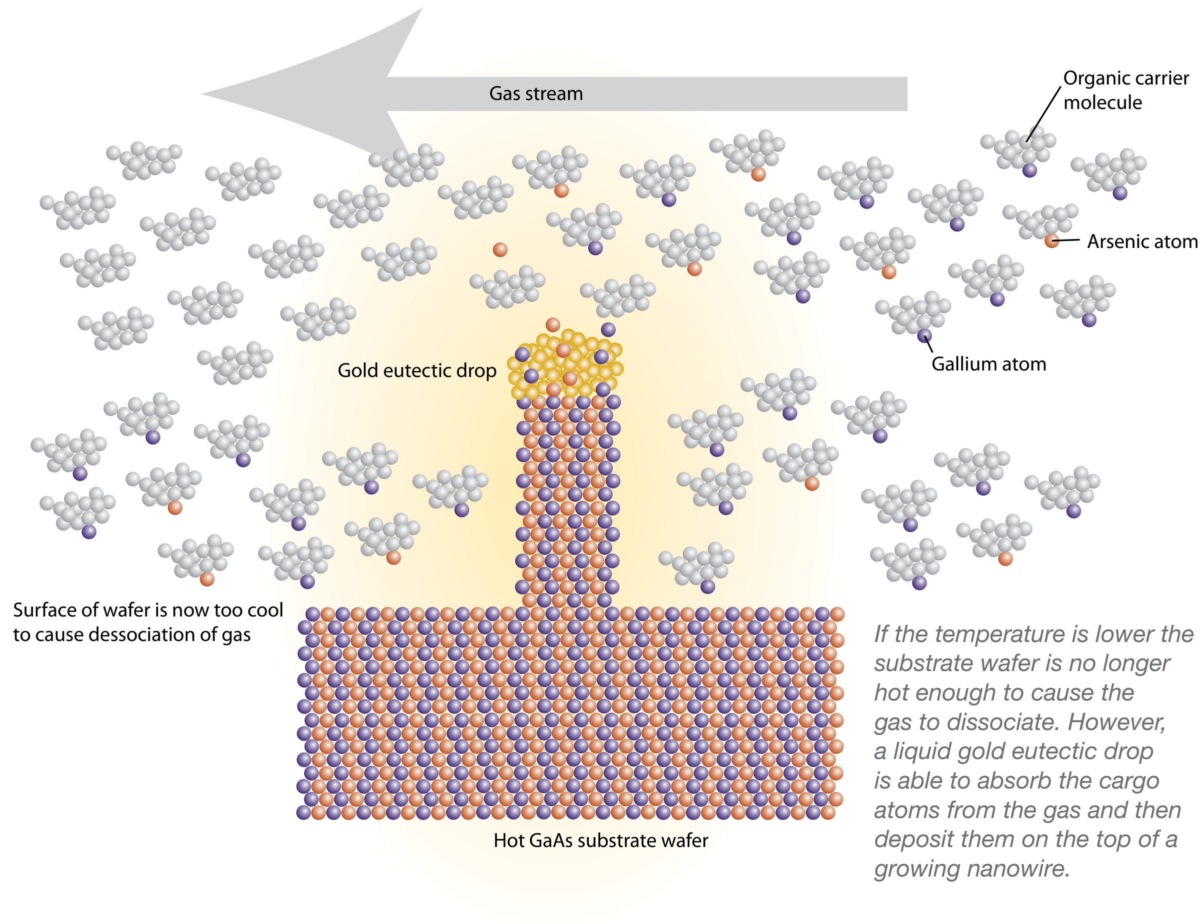
This is where something quite extraordinary begins to happen. The supersaturated eutectic begins to deposit these elements onto the wafer in the form of perfect crystal lifting the gold dot upwards as it goes. As the gases flow, these minuscule needles of crystal begin to rise from the surface with the gold eutectic cap on the top.

Just as with the large area growth, if you change the composition of the gases you change the type of crystal that's laid down under the gold eutectic drops. This makes it possible to build up different slices along the nanowire as it grows.

In this way it's possible to create long fine nanowires with multilayer mirrors at the ends and an active laser region in the centre. These will then function as nanoscale lasers.



Principle of an MOCVD reactor. The heat around the substrate wafer causes the metal organic gas molecules to dissociate depositing their cargo atoms onto the wafer surface where they settle to form a perfect extension of the underlying crystal lattice.



If the temperature is lower the substrate wafer is no longer hot enough to cause the gas to dissociate. However, a liquid gold eutectic drop is able to absorb the cargo atoms from the gas and then deposit them on the top of a growing nanowire.

Total recall

Holographic quantum memory becomes science-fact

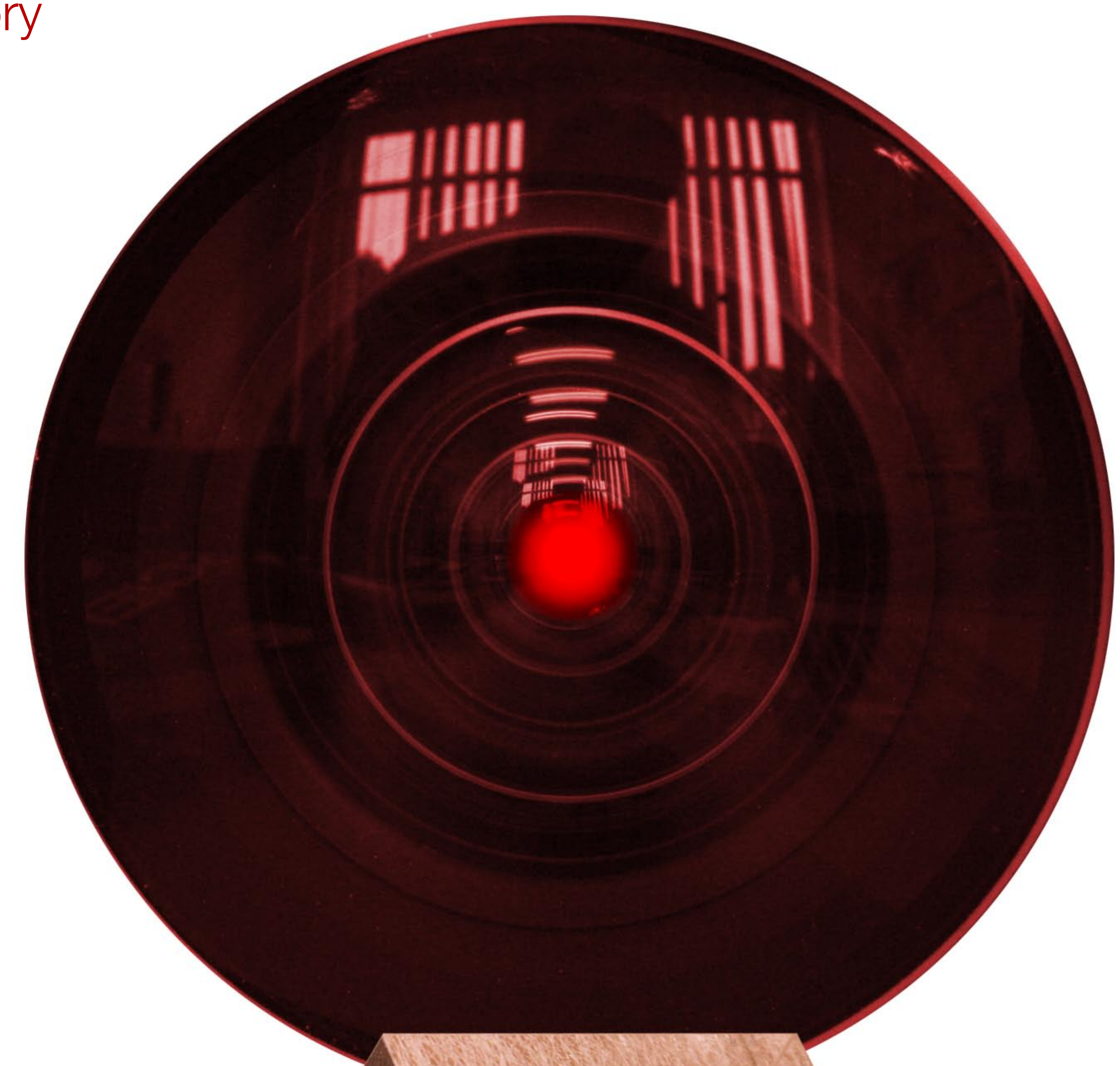
Quantum mechanics is possibly one of the strangest areas of physics. Central to the theory is the notion of wavefunctions; mathematical functions that describe the probability of a particle being in a particular position at a particular time. But it's not like there being a 50:50 chance of your car being in the garage on a Sunday afternoon, because the car will either be there or it won't. In the quantum world the car would exist at every possible place including the garage until someone looked for it. Then in effect, the universe would make up its mind and decide, yes it's in the garage or no it isn't.

Of course you could try to cheat by looking if the car keys were on their peg. Then you could infer that it must be in the garage without actually making any measurement on the car itself. The strange thing is that in the quantum world, the act of measuring the keys would also instantly collapse the car's wavefunction into a definite value no matter how far away it was. Physicists call this entanglement. A situation where the wavefunctions of two things are inherently linked so that a measurement made on one instantly affects the other.

Entanglement is an essential part of the concept of quantum computing. In an electronic computer such as the one I'm writing this article on, each of my letters is stored as electrons in transistors in the RAM. As long as when requested, the RAM gives back electrons from that location, it really doesn't matter if they're the original ones that went in or what their spin is. Just like money in the bank. You don't have to get the exact same dollar coins back that you deposited so long as you get back the right number of coins.

With a quantum computer that isn't the case. The extraordinary computational power that's potentially available hinges on the preservation of every detail of the quantum particles as they're stored and processed. An electron or photon submitted to the memory must be given back in an identical form, including any entanglement that it has with any other system.

Whilst in principle a quantum computer can be built using a variety of architectures based around electrons, atoms or photons of light, some very promising results have come from light based systems. Back in 2009, an ANU team lead by Dr Matt Sellars, were the first to demonstrate a working two qubit logic gate based on photons of light interacting with a crystal lattice. Since then the group have been developing a number of crucial quantum computer components, the most recent of which is a holographic memory again based on a perfect single crystal.



Above: HAL, the thinking computer in Stanley Kubrick's science fiction classic 2001, employed a holographic memory. Below: A real working holographic quantum memory crystal

In effect when a photon of light enters the crystal it interacts with deliberately added impurity centres in the form of praseodymium ions. The light is absorbed and its information transferred to the spin states of the particular ion that did the absorption. But because any of the ions within the crystal lattice could have done the absorption and you don't know which one, in effect all the ions in the crystal are now entangled.

But how do you then play back the photon? The key comes from the fact that the laser used to generate the "write" beam has a very, very narrow range of wavelengths, even by monochromatic laser standards. In fact the spectral range is so narrow that the chance of hitting the equally narrow absorption of any given ion is virtually zero. To get round this the scientists apply an electric field to the crystal. Atomic transitions shift in energy slightly when an electric field is applied, a phenomena known as the Stark effect. Because there are trillions of individual ions in the sugar cube sized crystal and because the applied field varies across it, the ion absorption energies form a gradient. And somewhere within that lattice will be some ions with the perfect absorption to match the incoming photon.

If the field is now reversed, the absorption process is reversed and the trapped photon is effectively released with all its entanglements intact. The really clever thing about this system is that because the crystal is very cold, close to absolute zero, the excited ion states are very stable. This means that they can potentially hold photons for hours. That might not sound like a particularly long time, but it's thousands of times better than can be achieved by any other method and plenty long enough for computational calculations.

"In effect what we have is a working holographic quantum memory" Dr Sellars explains, "It's really just a matter of the technological aspects being perfected."

Don't expect to be seeing a quantum processor in your next laptop, but the technology required to build these remarkable machines is, step by step, becoming reality.

Electricity – Carbon = Good

How maths may be the key to clean coal power

Australia currently generates around 85% of its electricity by burning coal, resulting in 170 million tones of CO_2 being pumped into the atmosphere each year. It's a major factor in making Australians the highest polluters in the world, ahead even of the US. Although alternative energy such as wind and solar is slowly coming on line, most realistic analysts agree that coal must continue to provide at least some of our power for the foreseeable future. But that's not to say that coal can't clean up its act. There are technologies available to extract CO_2 from the flues of power stations though many of these are far from economically viable.

However much the average person wants to save the environment most people and most industries are simply not in a position to pay vastly more for electricity than they currently do. So what we need are CO_2 extraction technologies that are simple, efficient and highly cost effective. And the only way we can achieve this is with some advanced science.

Dr Rowena Ball is an applied mathematician and physical chemist, currently working on the complex thermo chemistry and kinetics involved in flue gas carbon dioxide capture.

Carbon capture involves two main processes. The first is the "scrubbing", or selective removal of carbon dioxide from the mixture of flue gases in the emissions stream. The second is "sequestration" – the stable, long-term geologic storage of the compressed pure carbon dioxide. In collaboration with an Australian company, Calix Ltd, Dr Ball is developing a novel looping technique to scrub the flue gases of power stations.

The team is refining what's known as an Endex reactor, based on some initial work Dr Ball did back in the 90's. In the Endex reactor, carbon dioxide is adsorbed by calcium oxide to form synthetic limestone, a reaction that is exothermic, so generates large amounts of heat. The second stage is desorption of pure carbon dioxide from this limestone, a reaction which is endothermic so requires a lot of heat energy to drive it. The clever part about the Endex reactor is that the adsorption and desorption reactions are coupled thermally and matched kinetically, meaning that the energy generated by the exothermic first stage is harnessed directly to drive the endothermic second stage making the process highly energy efficient and therefore cheap.

"Calcium oxide is ubiquitous in the Earth. It very slowly adsorbs carbon dioxide from the air to form limestone. But at normal temperatures the process occurs only over millions of years, and is too slow to be of any use in blotting up carbon dioxide on time scales of interest to human responses to climate change." Dr Ball explains.

The Endex process operates between 750 and 850 degrees Celsius, with the carbon dioxide adsorption/desorption cycle taking only seconds to minutes. Perhaps most importantly, the system can be retrofitted to existing power plants, avoiding the cost of entirely new power stations.

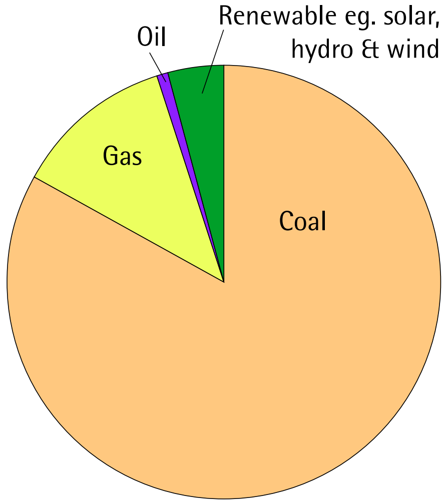
"Cost has been the big hurdle in flue gas carbon dioxide capture", says Dr Ball, "All the methods considered so far have been prohibitively expensive. Unless the capture step can be done for less than $10 per tonne of carbon dioxide captured, it is not going to be economically viable. Developing countries in particular are not going to be able to afford it."

The company has received support from both the Federal and Victorian Governments to build a large-scale demonstration Endex plant, which is currently under construction at a site in Victoria.

Although the development of the Endex process was facilitated by modern mathematical modelling methods and advanced computing, the underlying science has its roots in stability theory, developed during the late nineteenth century and early twentieth century. The original applications of this branch of mathematics were in celestial mechanics and control theory. Stability theory aims to answer the question: Given a dynamic system in a particular state, will a perturbation to that state grow or decay? In other words, is the system stable?

"The application to Endex carbon capture is an interesting example of how high quality fundamental mathematics research can turn out to have important applications to new problems," Dr Ball says. "In the late 19th century and for most of the 20th century fossil fuels were cheap, climate change was not a problem, and carbon dioxide capture had barely been heard of. Times have changed dramatically. This is a very good argument in support of mathematics and for training young people in the mathematical sciences."

Although there's a great deal of support for renewable energy, economic and technical factors make it likely that fossil fuel power plants will be around for the foreseeable future.



Australia currently relies heavily on coal for power generation

A positron approach

Antimatter in medicine

Compared to a century ago, doctors have a bewildering range of diagnostic and imaging techniques at their disposal one of which is the Positron Emission Tomography or PET scan.

In preparation for the scan the patient is injected with a sugar solution in which some of the hydrogen atoms have been replaced with radioactive fluorine 18 (^{18}F). This substitution is possible because fluorine and hydrogen both have a single electron in their outer shells giving them similar chemical properties. Once inside the body this radioactive sugar is taken up by cells. Highly active cells such as growing cancers absorb far more sugar than normal cells around them.

Because ^{18}F has a half-life of only a couple of hours, it soon decays inside the body emitting positrons (anti electrons). Because these positrons are antimatter, they rapidly annihilate when they meet electrons in the body. When this happens the resulting energy release is in the form of a pair of gamma rays emitted in almost exactly opposite directions. A ring of special detectors record these gamma rays. By calculating their directions of flight and time of arrival it's then possible to build up a three dimensional picture of the body.

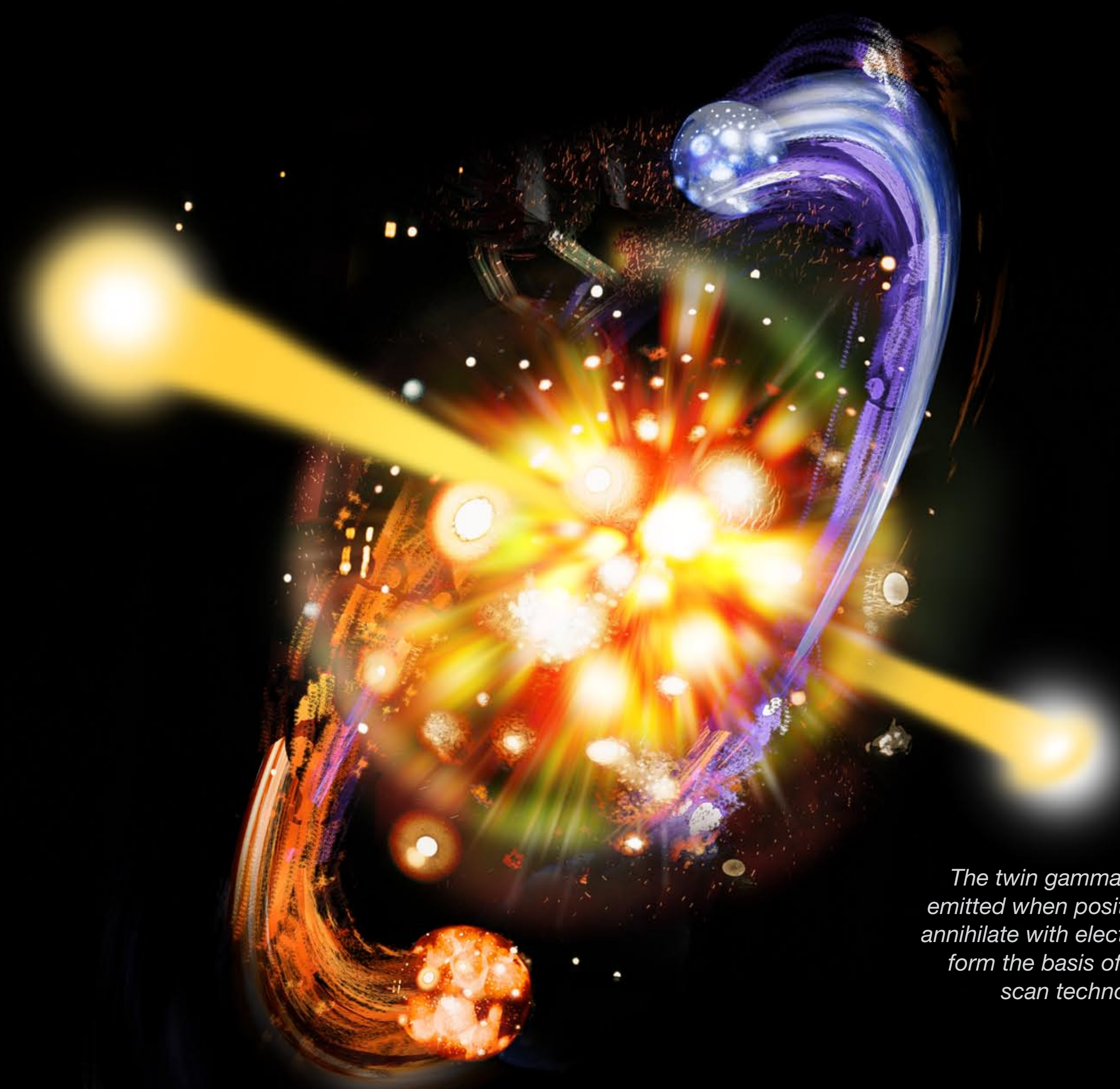
One the principal advantages of PET, is that it's a functional imaging technique enabling doctors to not only see structures within the body, but also which structures are the most active. However there are limitations too.

One of the problems is that the radiation dose received by the patient is roughly equivalent to their annual yearly limit. Another is that the positrons travel a little way from the fluorine atom that emits them before they decay, resulting in a significant loss of resolution.

The latter problem is due to the energy with which the positrons are emitted. Although the decay of ^{18}F produces comparatively low energy positrons, due to the relatively low density of human tissue, these still travel several mm before annihilating.

The best approach to fixing both these problems is to go back to the underlying physics and that's exactly what scientists like Dr James Sullivan from the Centre for Antimatter-Matter Studies are doing.

"One of the main problems in designing better PET scanners is that we still have quite a limited understanding of how positrons behave when they interact with matter. A lot of what we currently know about safe radiation doses is based on electron data yet positrons can behave quite differently." Dr Sullivan says, "We have to put a lot more physics into this and build a better understanding from the bottom up."



The first step in doing this was to look at the way in which positrons scatter from very simple atoms such as hydrogen and helium using the Australian Positron Beamline Facility at the Australian National University in Canberra. "This is very much a problem in fundamental quantum mechanics," Dr Sullivan explains, "The sensible approach is to begin with a system with as few variables as possible then build to more complex molecules, which might be useful in a more applied context."

One such molecule is pyrimidine from which the DNA bases cytosine, thymine and uracil are constructed. "There's been some quite encouraging results reported recently that suggest that the data collected from pyrimidine does indeed have direct relevance to the interaction of radiation with DNA, so we believe that we're on the right track here." Dr Sullivan says. "The long term goal of this work is to use this improved knowledge of the physics of antimatter to better understand the underlying process of PET scans - ultimately working towards better PET scanners than we have today."

The scientists are hoping that eventually this work will result in an increase in the resolution of PET scans, enabling them to see very small secondary tumours much earlier which should offer a better outcome for patients. A better understanding of how positrons interact with DNA will also lead to better defined radiation dose limits which should in turn, help reduce risk to patents.

The twin gamma rays emitted when positrons annihilate with electrons form the basis of PET scan technology

Playing time backwards

The rubidium quantum sequencer

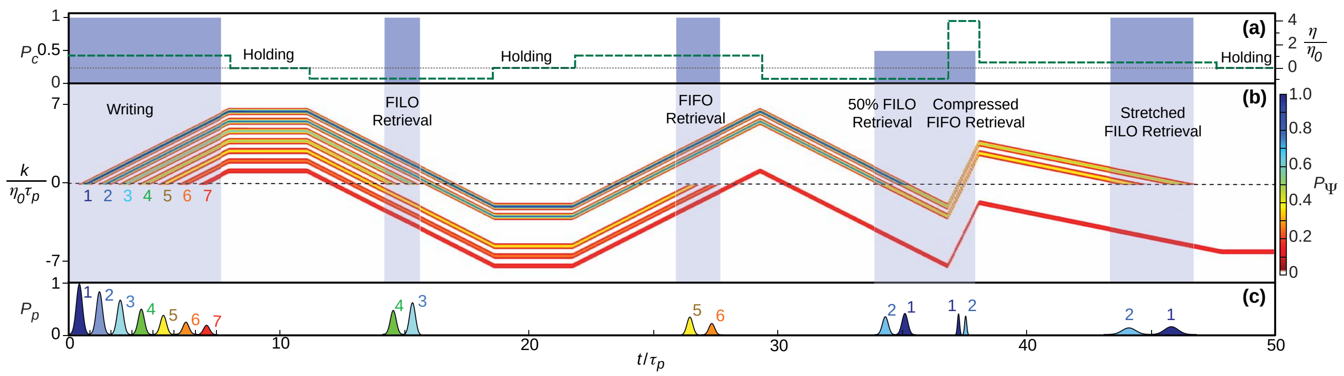
When an atom absorbs a photon, the usual scenario is that an electron is lifted from a lower energy level to what's known as an excited state. How long it stays there depends on the particular atom and the state but it can range from nanoseconds to minutes and even hours. What excites quantum physicists in this process is the ability to effectively store a photon in such a transition then release it later in the opposite process known as a photon echo. But in order to be useful in devices such as quantum memories and encryption systems, the coherence of the original photons must be maintained.

This is what distinguishes a true quantum memory from a simple detect and re-emit memory. You could simply count the number and timing of photons hitting a detector, store that information perhaps on a computer then regenerate the pulse using a laser diode. The problem would be that although the timing and amplitude of the pulses would be right, the phase information would be lost. This means that if the photon stored in the memory were one of a coherent pair, after it were released it would no longer generate an interference pattern with its twin photon.

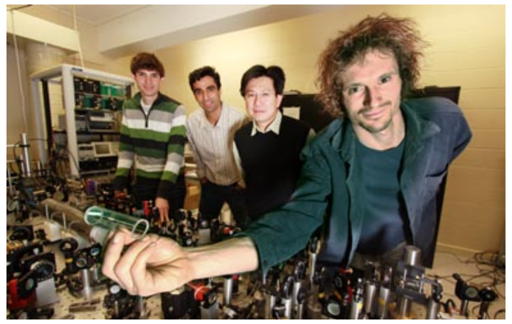
In a true quantum memory all of the information about the incoming pulse is stored. So a photon from a laser stored there will create an interference pattern with a second, un-stored photon from the same laser. And this is the kind of memory that's useful in quantum information processing.

Mahdi Hosseini, Dr Ben Buchler and Professor Ping Koy Lam from the ANU Department of Quantum Science are amongst a number of scientists around the world working on various types of quantum memory. In a recently released paper in the prestigious journal ***Nature***, they describe a new type of quantum memory based on rubidium vapour. This new memory can not only stores pulses with their coherence information intact, but is also able to split a single pulse into multiple parts, stretch and compress the length of the pulses and re-sequence the pulses so they can be recalled in any order. Recalling the pulses in any order could be useful as a random access memory for quantum information.

At the heart of the system is a sealed glass vessel with an optical window at each end, containing rubidium vapour and housed in a magnetic field gradient. Rubidium was chosen because its atomic structure has a hyperfine splitting in its ground state. In effect this means that there are two minimum energy electron configurations.



By varying the field within the chamber and turning the coupling beam on and off it's possible to in effect, shuffle the components of the pulse around, releasing them in a different order to that in which they entered.



Dr Buchler and members of the science team

"It is possible to generate a photon echo using just a two level atomic transition, but this limits you to storage times related to the lifetime of the excited state. With the three level rubidium system we can in effect, move the excited electron to a second very long-lived storage state using a bright control laser. This also means that if we turn that control laser off, the electronic state is effectively frozen." Dr Buchler explains.

When the laser pulse enters the chamber the rubidium atoms are excited and the pulse is absorbed. The atoms then begin to "spin". Each atom spins with a different speed that depends on the initial frequency of the atom, which is controlled by the magnetic field. Because the atoms all spin at different speeds its statistically almost impossible for them ever to realign to the point they were all at when the pulse entered. It's a little bit like setting the combination on a safe then spinning the dials at different rates. No matter how much you keep spinning them, they're never likely to coincidentally realign and open the safe.

"What we would really like to do to get the pulse out, is to turn time backwards," Dr Buchler explains, "But of course we can't do this. What we can do though, is reverse the external magnetic field. This sets the spins into reverse and after a given time they'll be right back where the absorption occurred."

When this happens the dipoles are all aligned in the exact same way they were during absorption and the moving charges generate the right electromagnetic field for a photon. The net result is that a photon is re-emitted with exactly the same phase frequency and amplitude as the one absorbed. And it has retained all it's quantum mechanical coherence information. It's almost like spinning the safe combination dials backwards in exactly the way they went forwards. After a set time you hit the right combination and the safe can be opened.

However, in the case of the rubidium gas chamber, the photon release requires both the right spin combination and the control beam to be on. If the control beam is off the electrons have no way of getting back into the appropriate ground state so no photon is created even if the spins are aligned. In terms of the safe, spinning the locks backwards will get you the right combination, but it is the control beam that provides the energy to open the door.

"This gives us the ability to send a sequence of pulses into the gas chamber, absorb them all, then by switching the control beam on and off as we reverse the field, select which ones are re-emitted and which are not. And of course we can then flip the field and run the spins forward again, then backwards and so on. In this way we can store the pulses and re-emit them in any order or sequence." Dr Buchler says.

The optical table on which the memory runs is a maze of hundreds of components but the basic principle is more ingenious than complex. "Actually the experiment was shockingly simple. We had the idea at our group discussion in the morning and because the lab was largely set up, we were seeing the first results that afternoon."

These latest experiments are the PhD work of Mahdi Hosseini who began working in the ANU quantum optics group just a year ago. He expects to push the technique even further in the next two years by investigating the storage of single photons and other quantum states of light.

Creating your own space

New space simulation facility gets go-ahead

Even though spacecraft represent an ultra modern technology, the essential physics that drives their motion dates way back to the seventeenth century and Sir Isaac Newton. Newton's third law tells us that for every action there is an equal and opposite reaction. So when you fire a gun the bullet moves forward and the gun recoils backwards. Rocket engines operate on the exact same principle. Propellant is thrown out of the back and because momentum has to be conserved, the rocket moves forwards.

However, not all rockets are created equal. An engine that throws its propellant out very quickly generates far more momentum and therefore far more thrust for each kg of propellant used, than one that does so slowly. Each kilogram of propellant you burn in space requires about ten kilograms of propellant to get it up there, so efficiency in propellant use is something that space engineers care very much about.

The problem with conventional chemical rockets is that there is a limit, set by thermodynamics, to how fast gas can be ejected which is around 3000 ms^{-1}. Another way to eject propellant is to ionize a gas and use an electric or magnetic field to accelerate it. This can achieve exhaust velocities of ten or even a hundred times higher than those of a chemical rocket, so the precious propellant is used far more efficiently. This makes plasma (ionised gas) thrusters the technology of choice for manoeuvring satellites or long space missions.

A new type of plasma thruster has recently been developed by Professor Christine Charles at the Australian National University. This HDLT (Helicon Double Layer Thruster) offers several advantages over conventional plasma thrusters not least of which is its simple robust design that should offer much higher reliability than existing units.

Unlike a conventional ion drive, the HDLT ejects both positive ions and electrons in its exhaust. This avoids charging effects on the spacecraft and also eliminates the need for separate electron ejecting neutralisers, that are one of the most common sources of failure on existing ion thrusters.

The HDLT has attracted attention around the world and currently forms part of a collaboration between Ariane rocket manufacturer ASTRIUM, the satellite arm of the European Aeronautic Defence and Space Company (EADS) and the ANU. But one of the problems with building revolutionary space systems is how to test them. It costs many millions of dollars to launch any spacecraft and naturally no one wants to be the first to run an untested manoeuvring thruster on their satellite, however promising it may be.

The answer to this is to build a facility on Earth that can simulate the environment of space well enough to be able to refine the thruster design and establish its reliability. Recent funding from the Australian Government will allow the HDLT team to do just this.

The Advanced Instrumentation and Technology Centre at Mount Stromlo Observatory is rapidly becoming one of the most advanced astronomical instrument and spacecraft assembly facilities in the country. So it makes perfect sense to build the new simulation facility there, along with many other space related facilities.

Essentially the new test facility will be a large tank that can accommodate the test thruster and be pumped down to a vacuum approaching that of space. But this is a more complicated task that it may first appear. The problem with a plasma thruster is that it spews ionised gas out into the chamber. If this accumulates in any quantity it makes the environment within the chamber less space-like and distorts the results of the tests. Consequently, the test facility has to have the fastest and most efficient pumps available to maintain good vacuum as the thruster runs. Achieving such a vacuum begins with simple rotary pumps then turbo molecular pumps, like miniature jet engines, then finally cryopumps. A cryopump works by cooling an active area down to close to absolute zero so that any gas that comes into contact with this liquefies or freezes instantly. This is a very effective way to remove residual gas and troublesome contaminants like water and oils from a high vacuum system.

Another stress that spacecraft face is thermal cycling. As they pass the sunlit side of the Earth they heat up then as they are plunged back into the freezing cold of the Earth's dark side they cool down again. This can happen every few minutes depending on the orbit and the resulting repetitive expansion and contraction can easily cause components to fail. To simulate this in the test facility, the tank will contain huge shrouds that can be heated or cooled with liquid nitrogen. In this way a prototype device can be exposed to such thermal cycling then removed and examined for signs of failure. A luxury that engineers never get on spacecraft in actual orbit.

The new test facility is expected to be operational by the end of 2012 so that actual flight testing of the HDLT thruster can begin in 2013/14.

Professor Christine Charles watches a prototype HDLT being tested in a space simulation chamber

Core business

Successfully transferring technology from the lab to industry

Modern hospitals are generally equipped with an X-ray CT scanner - a machine that takes an X-ray of the body from all angles then compiles the images into a three dimensional picture. It's an amazing diagnostic technology but its application isn't restricted to medicine. Such techniques are equally useful in imaging scientific specimens. However whilst a resolution of a millimetre or so may be adequate for diagnosing disease and injury in something the size of the human body, science is often dealing with much smaller samples with much finer structure.

This was exactly the situation back in the late 1990s when researchers from Applied Maths in the Research School of Physics and Engineering began investigating the fundamentals of fluid flow in porous materials including ink on paper and oil in rocks. In each case, the fibres and pores respectively are very small yet their organisation determines critically how fluids behave when they come into contact with the material. Having looked at the limited range of commercial machines available to analyse such samples, the researchers decided to build their own!

The prototype scanner was capable of very much higher resolution than a typical hospital scanner and enabled the mapping of small samples in unprecedented detail. But of course generating the x-ray data is only half of the battle. They also had to create a vast suite of software that would turn the huge volumes of data into an accurate and useful 3D model of the sample.

In time all the hard work paid off. Not only did they have a unique and useful scientific tool, their scanner and its software began a chain of events that would ultimately lead to the formation of a multi-million dollar company.

The establishment of an international industry consortium of the world's largest oil and gas companies drove the researchers to focus on the analysis of porous rocks such as those that house oil and gas reservoirs. The proportion of solid to void and the way those voids are interconnected make an enormous difference to the way fluids like oil, gas and water flow through rock. And if you're in the petrochemical business, flow characteristics are one of the most important factors in setting up a profitable drilling operation.

Realising the potential usefulness of the new scanner and software to the petrochemical industry, the University set up a spin-off company called Digitalcore to commercialise the technology.

"It took over 18 months to set the company up and on our first business day in May 2009 we had one and a half staff, an office and no work!" Digitalcore CEO Dr Victor Pantano says. "It was very tough for the first 18 months but now we are getting a steady stream of orders coming in and the company is beginning to grow."

In March 2012 Digitalcore announced a merger with Numerical Rocks AS of Trondheim Norway – another spin-off company involved in rock analysis. Together they will form a company with offices in Australia, Norway, the US and the Middle East.

"As the price of oil has increased over the years, it has become commercially viable to exploit the more difficult reservoirs and especially to tackle what's known in the industry as unconventionals," Dr Pantano explains, "That includes things like shales and tight gas sands."

"Whilst there are alternative methods for characterizing core samples from rock, the only way to get reliable data in many of these unconventional reservoirs is using the techniques that we've been developing. Much of Digitalcore's growth in the coming years will be based on the analysis of samples from unconventional reservoirs."

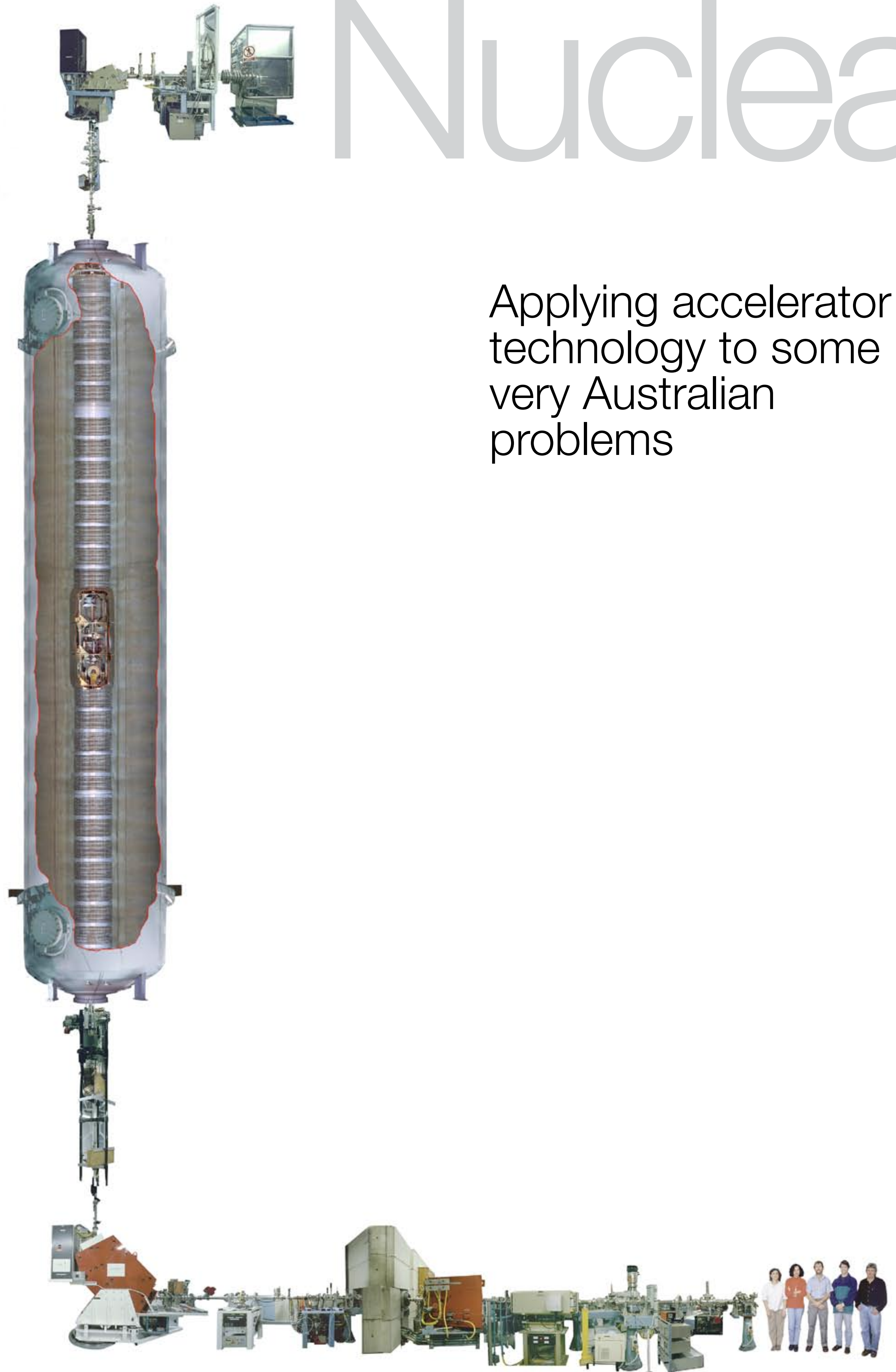
Ironically one of the greatest difficulties the company currently faces is recruiting skilled people. "The resources boom means that graduates in the geo and petro areas are in high demand so it's hard to get enough people to fill the positions we have available."

One novel solution has been to recruit under-graduates from the University to undertake the scanning and basic image processing work. "This scheme has provided us with high quality people to undertake much of the pre-analysis work and gives the students an income stream and perhaps more importantly, hands on experience in a booming industry." Victor says.

Working together, Digitalcore and the University have managed to secure several millions of dollars of research funding to continue fundamental research into instrument design and novel computer algorithms while branching out into new application areas such as coal and CO_2 sequestration. The researchers continue to maintain a vibrant and active international industry consortium which is unique within the University.

Digitalcore is an excellent example of how advanced science and technology can, in the right hands, make the transition from the lab to a commercially viable business venture which benefits both industry and the University.

Nuclear solution



Applying accelerator technology to some very Australian problems

Left: Some members of the AMS team with the accelerator to scale

The Australian National University hosts Australia's largest and most powerful nuclear accelerator, the 14UD. Inside its massive concrete and steel tower, a charging chain raises the potential of a central electrode to +15 million Volts. Negative ions created at the top of the tower are strongly attracted to this and accelerate towards it through an evacuated pipe in the accelerator's core. At the peak potential the ions hit a microscopically thin carbon foil which strips off some of their electrons changing their charge from negative to positive. The now positively charged ions are repulsed by the positive central voltage and so are further accelerated as they leave.

At the bottom of the tower a huge magnet bends the ion beam and directs it into any one of several target lines at the end of which are a variety of nuclear physics experiments. Two of these belong to Professor Keith Fifield's Accelerator Mass Spectrometry group.

Conventional, low-energy mass spectrometry exploits the fact that ions of different mass are bent at different angles in a magnetic field rather like the colours of light are split by a prism. In its crudest form, mass spectrometry simply enables elements of different masses such as say iron and cobalt to be separated. However the addition of the massive 14UD accelerator, coupled with techniques derived from fundamental nuclear physics research for identifying ions of the same mass but from different elements, makes the ANU system so sensitive it takes the concept to a whole new level.

Not only can this Accelerator Mass Spectrometry (AMS) system separate different isotopes of the same element and different elements with the same mass, but it also has the sensitivity to make reliable measurements on samples containing incredibly low concentrations of those isotopes. This makes it one of the most powerful tools for nuclear forensics anywhere in the world, attracting scientists from many countries to come here and use the facility.

But other than enhancing our credibility in international science, how does this kind of technology directly benefit Australia?

One of the cornerstones of our economic prosperity is agriculture and in a dry country like ours, one of the greatest threats is erosion. Many of Australia's agricultural soils are very old, and are being replenished at very low rates by natural processes. Modern agricultural practice aims to conserve this valuable soil, but the effectiveness is difficult to assess without a method to measure the rates of soil loss and deposition. AMS can provide just such a method with a little help from what seems like a very unlikely source; the nuclear weapons tests of the cold war era.

During the 1950s and 60s there were literally hundreds of atmospheric tests of nuclear weapons. These introduced plutonium into the Earth's atmosphere in small quantities. Dispersed across the entire surface of the Earth by stratospheric winds, this plutonium eventually fell to earth where due to its chemical properties, it bonded strongly with soil particles.

It is nowhere near as horrendous as it sounds because away from the immediate vicinity of the test sites, the concentrations are so incredibly small that the resulting radioactivity makes essentially no difference at all to the Earth's natural radioactive background. The Plutonium's presence is however, measurable using a super sensitive technique like AMS.

"We have a fairly clear picture of the isotopes of plutonium that were created by nuclear testing and the way they were distributed," Professor Fifield says, "So when we find less plutonium than expected in a soil sample we can say with some confidence that the area has experienced significant erosion since the 1950s."

The ANU team has successfully applied the technique in the prospective Daly Basin agricultural area in the Northern Territory, and in Canberra's water catchment following the 2003 bush fires and subsequent torrential rains. But it's not just the study of Australia's recent history that can benefit from AMS. The technique also has applications over a far longer timescale.

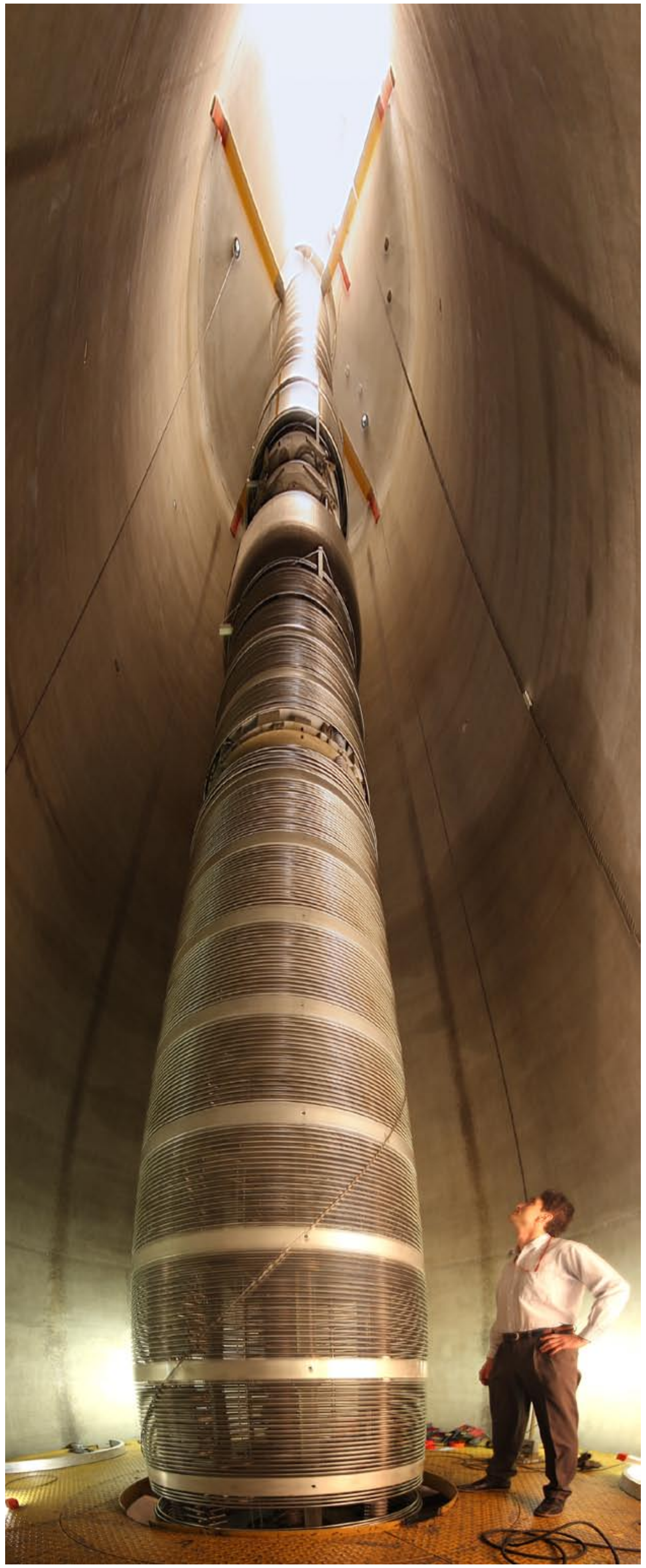
Ever since the solar system formed, the Earth's atmosphere and surface have been constantly bombarded by cosmic rays. These energetic particles from space occasionally score a direct hit on an iron nucleus within a rock.

This can transmute the iron into an isotope of manganese, ^{53}Mn which has a half-life of around 3 million years. In an environment with no erosion at all, the ^{53}Mn builds up in the surface rock until the production and decay rate are equal. If the rock surface is however being slowly worn away, ^{53}Mn is being lost to erosion and the concentration of the isotope is lower by an amount that is proportional to the erosion rate. Alternatively, if the surface has only been exposed for less than a few million years, then the concentration of the ^{53}Mn isotope is a measure of the length of time since first exposure.

Although the long half-life is a bonus when it comes to using ^{53}Mn as a geological marker, it does mean that the rate of radioactivity associated with its decay is very low. This would make it impossible to detect using methods that rely on detecting the emission of decay products. However since AMS directly measures the presence of the isotope by counting ^{53}Mn atoms, this presents no problem at all. "We're able to measure reliably concentrations corresponding to one atom of ^{53}Mn in 100 million million atoms of iron!" Professor Fifield says, "This is equivalent to finding 20 grains of sugar in the Melbourne Cricket Ground filled to the brim with salt."

The technique is well suited to Australia, because many of our landscapes are richly endowed with iron rich rocks at the surface. Such ^{53}Mn measurements complement the measurement of other isotopes by the group in their studies of soil erosion and exposure dating of landscape surface features. Taken together the work provides a valuable source of data to test climate change models. For instance, it can be used to date the formation of desert features, the advance and retreat of glaciers, and the effects of changes in rainfall.

It's yet another example of how a country built on primary production can benefit by also having world-class scientific research program.



Inside the 14UD accelerator. When operating, the massive tank is filled with an insulating gas that prevents the 15 million Volt potential at the central terminal arcing across to the walls

Australian National University

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