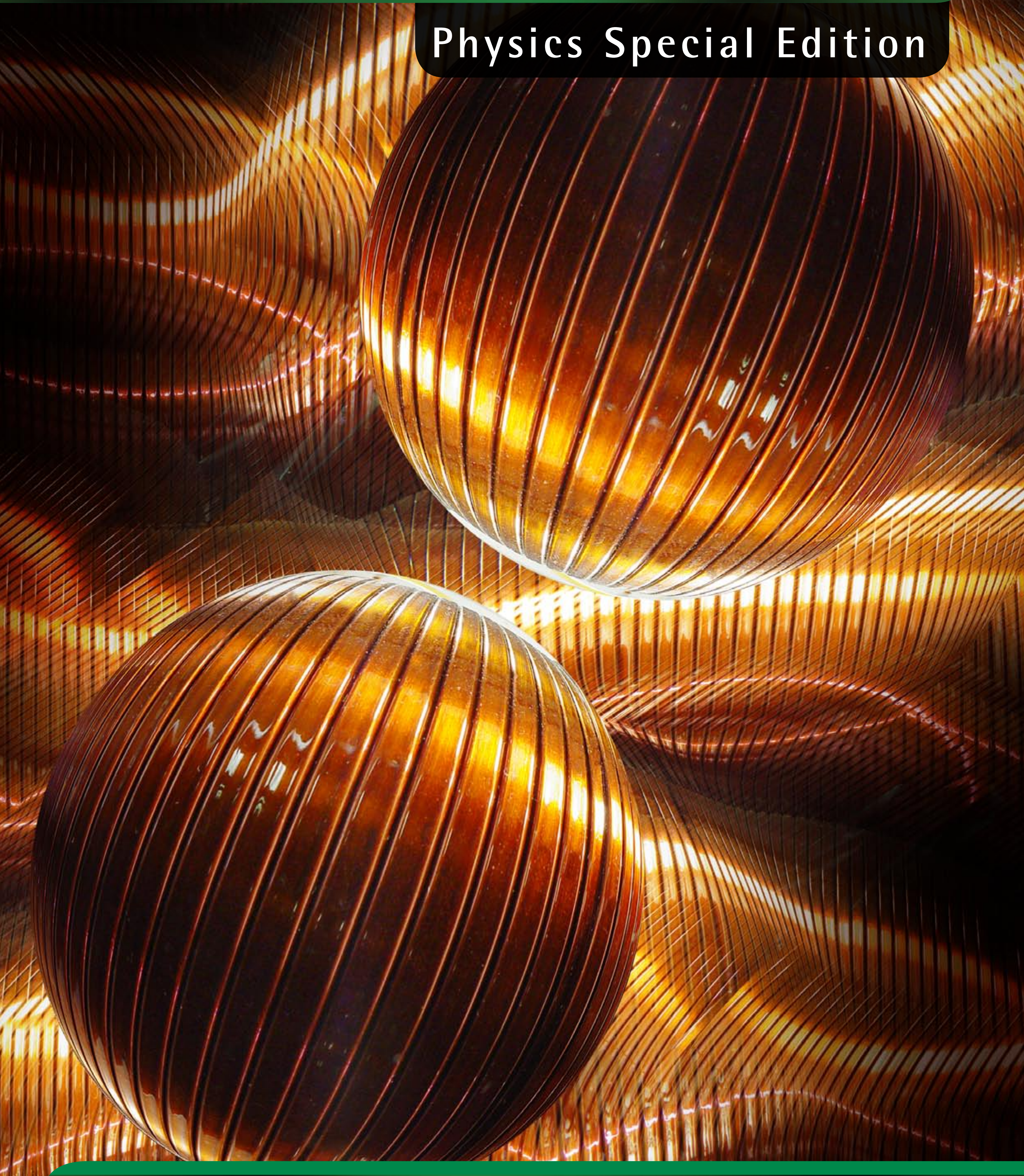
ScienceWise

SCIENCE MAGAZINE OF THE AUSTRALIAN NATIONAL UNIVERSITY

THE AUSTRALIAN NATIONAL UNIVERSITY

Physics Special Edition



http://sciencewise.anu.edu.au

The Editor's Corner

Welcome to the Physics Special

Dr Tim Wetherell

Essentially, the science of physics is about understanding the nature of the universe from the discrete particles that make up matter and force to large complex systems like planets and human beings. In this sense it could be argued that all science is underpinned by physics. If you understand the building blocks of nature and how they interact, then in principle at least, you are capable of understanding everything.

Of course it isn't always helpful to break scientific problems down to the level of bosons and fermions. But the continuous line of reasoning that physics provides from basic concepts to complex systems is what makes modern physics such a rigorous, effective and powerful tool for understanding and shaping the world around us.

At The Australian National University we strive to conduct world class fundamental, strategic and applied research in physics and its related disciplines in what is one of the largest and most comprehensive physics research activities in the southern hemisphere. Some of this research is theoretical physics such as string theory and various aspects of quantum mechanics. Some is highly applied materials science investigating improvements in semiconductors, lasers and detectors and their fabrication into novel devices. And yet more concerns 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 many major national experimental facilities such as 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. This outstanding research infrastructure is unique within Australia and is essential in providing a suitable environment in which to conduct research.

Above all, people are the most important element in any research activity and we are fortunate in having outstanding research leaders heading up our various activities. We also work hard to attract the best and brightest of students at both the graduate and undergraduate level and to provide physics education programs at the highest international standards. In doing so, we hope to ensure continued success in the future not just for our own university but for the entire discipline of physics.

It's not practical in one magazine to cover all of the physics research at ANU, but I hope this short collection of stories gives some sense of the quality and diversity of the work that goes on here.

ScienceWise
Science Magazine of The Australian National University

Physics Special

Managing Editor
Dr Tim Wetherell
T +61 2 6125 0361
E tim.wetherrell@anu.edu.au

Hairy Electrodes for Green Cars

How Plasma Technology Promises to Greatly Reduce the Cost of Fuel Cell Manufacture

During the past few years there has been much talk in the media about hydrogen-powered vehicles providing a green alternative to petrol engines. Some cities such as Perth, have even introduced trial hydrogen busses on their regular routes. But one of the current obstacles to this green revolution is the high cost of hydrogen fuel cell power plants.

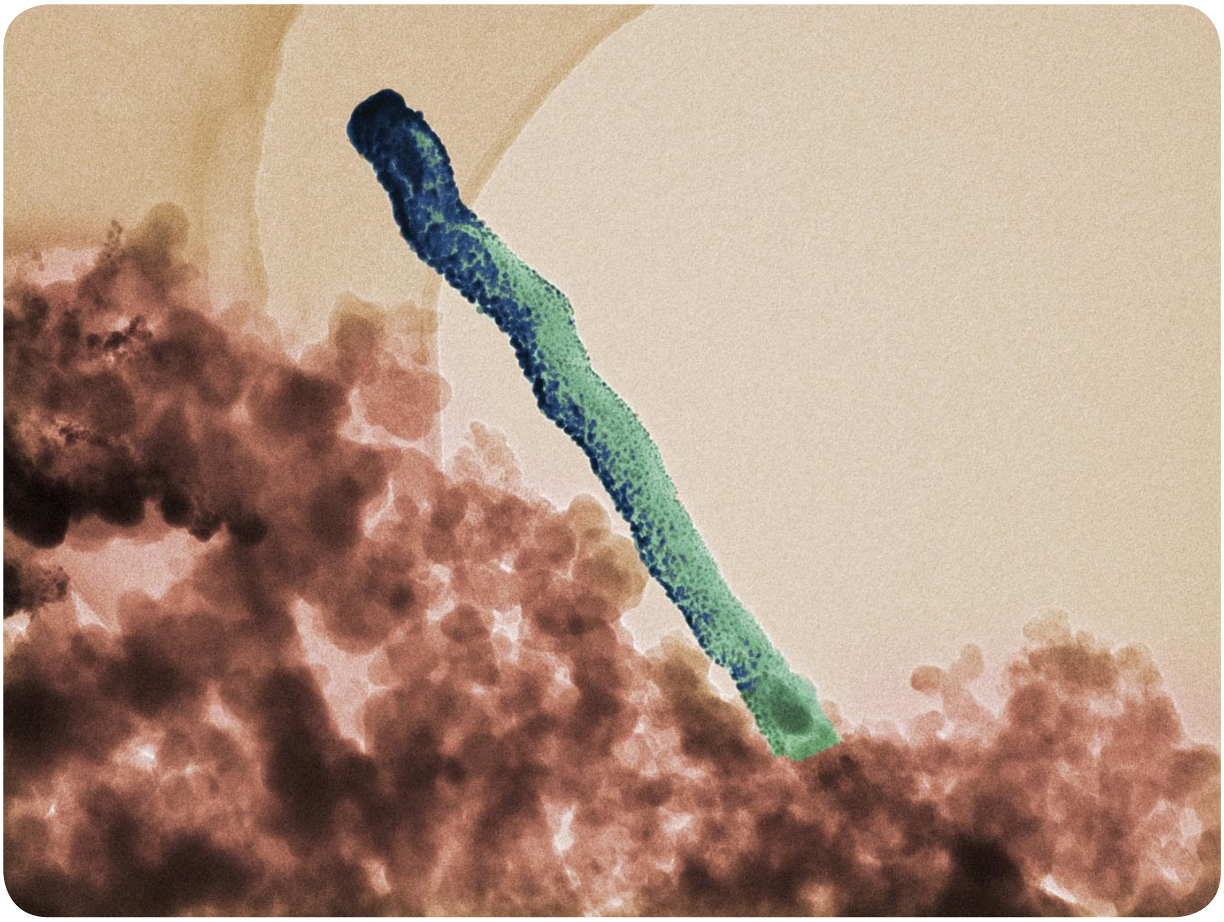
A fuel cell is a device for converting fuel, usually in the form of a gas, directly into electricity. There are many possible forms of fuel cell, but proton exchange membrane (PEM) cells are widely seen as the most promising option for road vehicles. In a typical transport PEM cell, hydrogen and oxygen gas are fed to catalytic electrodes at opposite sides of a special membrane that is porous to protons but not electrons. The protons and electrons are separated by the action of a platinum catalyst in the electrodes. The protons can diffuse directly through the membrane but the electrons have to make their way through an external circuit to reach the other side, providing power for an electric motor in the process.

Current PEMs typically employ a membrane of Nafion, a sulfonated tetrafluorethylene copolymer developed by DuPont. The problem with both Nafion and platinum catalysts is that they're very expensive to produce.

Professor Rod Boswell and the Space Plasma, Power & Propulsion Group at ANU have been working with plasmas for many years and recently became interested in the possibility using plasma deposition technology to dramatically reduce the cost of making fuel cells. "Production of current cells frequently relies on wet chemical stages which are messy, inefficient and consume large amounts of expensive materials. Our aim is to develop plasma based techniques to create both the membranes and the catalytic electrodes needed in fuel cells." Professor Boswell says.

The group has had a number of recent successes in production of both membranes and catalytic electrodes.

The manufacture of electrodes begins with a substrate of carbon paper; chosen because it's both porous to the gaseous fuels used in the final cells and is also an excellent conductor of electricity. This is loaded into the plasma reactor chamber



False colour transmission electron micrograph of platinum deposits on carbon nanostructures. The platinum is blue in this illustration.

Dr Christine Charles, Dr Cormac Corr, Cameron Samuell (Honours student), Wes Cox (PhD student) and Daniel Higginbottom (PhB student) with a hydrogen powered vehicle being developed to test the novel nanostructure fuel cells

and a very fine layer of nickel is deposited on the surface. Under the right conditions the nickel forms nanoscale droplets all over the carbon surface. The next stage is to introduce methane and hydrogen into the plasma chamber. Many complex reactions ensue leading to a very surprising situation where carbon complexes diffuse through the nickel seeds to form multi-carbon complexes below. The highly reactive hydrogen protons in the chamber etch away any carbon atoms that aren't strongly bonded to each other. The practical upshot of this is that carbon nano fibres grow below the nickel droplets lifting them from the substrate as they extend. The result is a carpet-like covering of carbon nanofibres on the paper.

Once the forest of nanofibres has been created the next step is to sputter coat the surface with platinum. "During the sputtering process the nanofibre tips get thickly coated with platinum with the droplets becoming progressively sparser further down the fibre. It's very much like snow falling in a forest, a lot gets deposited on the tree tops which greatly reduces the amount on the ground." Professor Boswell explains.

The tremendous advantage of this nanotechnology electrode is that its vast surface area and microscopically thin platinum coat reduce the amount of platinum required to about 15% of that in a conventional electrode of the same power specification.

The group has also succeeded in creating proton membranes by plasma decomposition of Trifluoromethanesulfonic (triflic) acid on a silicon wafer substrate. The finished membrane being detached from the wafer at the end of the process so it can be used for the next growth.

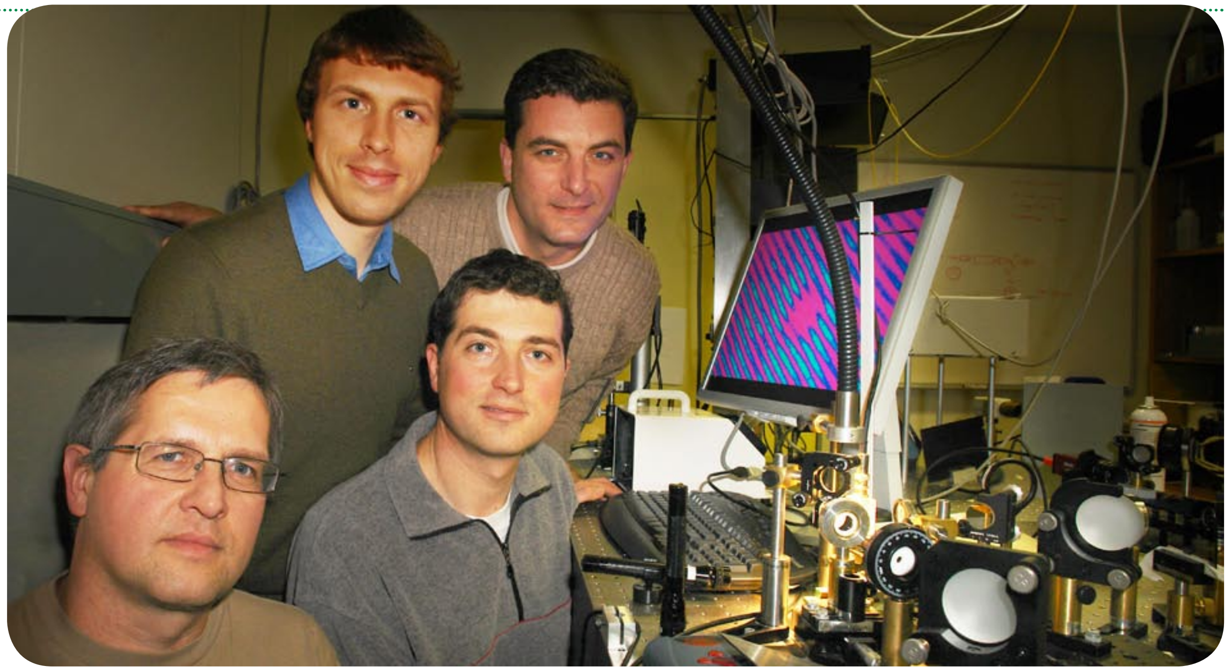
To make the finished fuel cell, the membrane is sandwiched between the hairy sides of two of the carbon catalytic electrode sheets and the whole assembly is hot pressed into a single sheet.

The new fuel cell technology is exciting stuff and may well be a key part of the transition to clean transport. But professor Boswell warns, "It has to be a holistic approach to clean transport. If you buy a cylinder of hydrogen today, chances are it was made from fossil fuels – it would be better to just burn the fossil fuel directly. What we need are fuel cell vehicles running on hydrogen that is in turn generated by clean electricity from solar or hydro. Then we'd be getting ahead."

At the moment it costs about six times as much to run on hydrogen as petrol. However, with petrol costs continuing to climb and the possibility of economies of scale in hydrogen production and distribution, it may not be all that long before that economic balance shifts.

Observing 2D Bloch Oscillations

90 Years After their Discovery, Bloch Oscillations are Seen in the Lab



Some members of the research group L to R: Wiesiek Krolikowski, Andrey Sukhorukov, Dragomir Neshev and Anton Desyatnikov

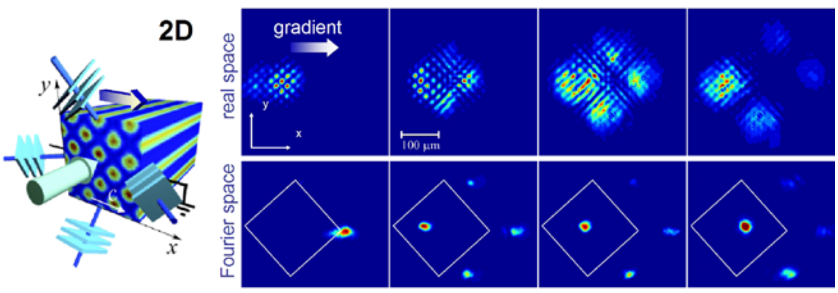
Some important scientific theories have become established and accepted by indirect observation of phenomena they create, because the underlying fundamental process can't itself be directly observed. For example planets orbiting distant stars are detected by the star's wobble not by direct observation of the planet. Whilst undoubtedly of great value to science, such indirect observations are often not just quite as exciting as the first actual photograph of such a planet was.

In a similar way the phenomena of Bloch oscillations and Zener tunnelling, theoretically predicted in the 1920s, are now a firmly established part of our understanding of solid state physics despite the fact that until now, no one has been able to directly observe them.

Bloch oscillations are phenomena experienced by electrons moving through a periodic lattice under the action of an external force. A perfect example of this is the flow of an electric current through silicon when a voltage is applied. If the same electrons were flowing through space under the influence of the same voltage they would simply accelerate and gain energy in a uniform manner. However the presence of a regular pattern of potential dips and humps created by atoms of the crystal lattice leads to some interesting phenomena.

There are some energy values the electron can't have because of resonance with the lattice. These forbidden energies lie within what physicists call band gaps. As the energy of accelerating electrons approaches the gap edge, they are strongly back scattered by the lattice. Such acceleration and back scattering causes electrons to wobble back and forth in space, an effect called Bloch oscillations. Of course if moving electrons are backscattered in this way and just wobble back and forth one might ask how conduction is possible at all? The answer lies in Zener tunnelling. Some electrons are able to quantum tunnel across band gaps, thus enabling overall movement.

Understanding the basic building blocks of solid state physics, including Bloch oscillations and Zener tunnelling, enables us to build computers, mobile phones and every other modern



Left: Optically induced two-dimensional lattice in a biased photorefractive crystal with optically imposed index gradient. Right: Real and Fourier space of the output beam monitoring different stages of a Bloch oscillations. The white square depicts the first Brillouin zone. The light inside the square is the oscillating part, while the three parts outside are tunnelled radiation. The arrows indicate the direction of the index gradient.

device. Despite this, until now there has been no direct observation of either phenomena because it is impossible to directly observe the motion of individual electrons in a lattice. However, in a collaborative effort between ANU and the University of Jena, a group of researchers have recently become the first scientists in the world to directly observe Bloch oscillations and Zener tunnelling in two dimensional structures by employing nonlinear optics and a bit of lateral thinking.

Essentially their idea was that since you can't observe electrons in an atomic lattice why not look at photons in an optical lattice? Wave particle duality is one of the basic postulates of quantum mechanics and it tells us that any particle can behave like a wave and visa versa. So the physics and mathematics that describe electrons in a periodic potential are similar to those describing light in an optical potential. However, unlike electrons, it is possible to make direct measurements of both the spatial distribution and momentum of light emerging from a lattice. The latter measurement is vitally important, because the momentum of propagating waves/particles is what governs how they interact with the lattice they are moving through. One of the nice features of optics is that a simple spherical lens produces a Fourier transform of a wave profile forming an image of the momentum distribution of that wave.

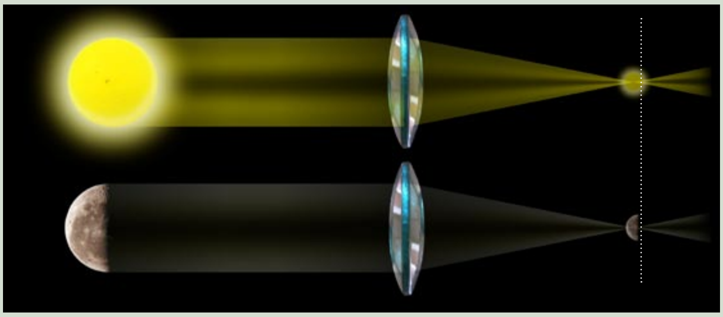
The researchers created a two dimensional optical lattice by generating a stationary laser interference pattern in a nonlinear material. The pattern of bright and dark spots modifies the local optical properties of the material inducing a regular series of regions with high and low refractive index. This means that a light beam passing through the material can experience a periodic lattice of a very similar type to that experienced by electrons passing through the regular rows of atoms in a crystal such as silicon. The nonlinear nature of the optical material also enabled the scientists to generate the equivalent of the voltage difference across a crystal needed to generate Bloch oscillations. By superimposing a smooth intensity gradient on the interference pattern used to generate the lattice, they were able to create a refractive index gradient which in effect, accelerates light in a similar way to electrons in a potential difference.

As expected, the results confirm the long established theories of Bloch and Zener. However, they also reveal many interesting and surprising complexities that arise from the lattices of higher dimensions.

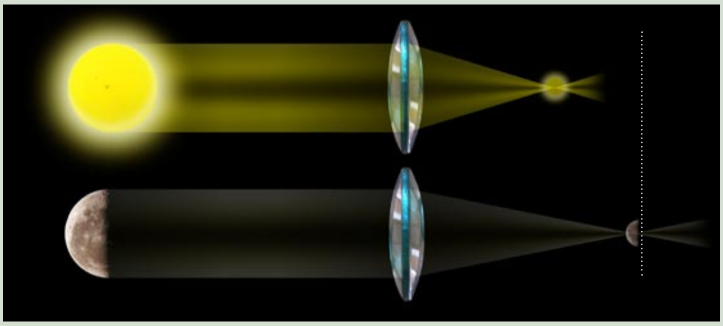
What Are Nonlinear Optical Materials?

The refractive index of a material is a measure of its ability to bend light. Glass has a larger refractive index than air so light passing from air to glass is bent. If the glass is correctly shaped, this phenomena enables us to create a lens that will focus a sharp image of a distant object such as the sun or moon.

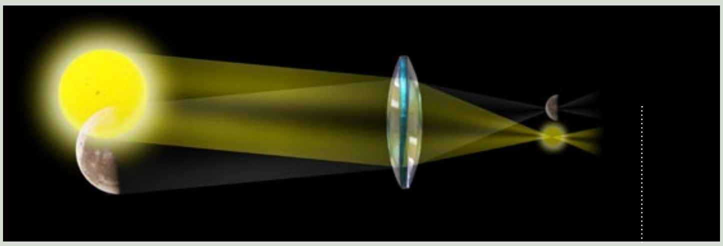
With normal linear materials such as those magnifying glasses and camera lenses are made of, the amount of bending, and thus the focal point, is the same regardless of the intensity of the light passing through them. So an image of the bright sun and far dimmer moon both come to a focus at the same point.



However with a nonlinear optical material, intense light alters the refractive index and thus the focusing properties of the lens. This means that the brighter light of the sun would alter the properties of the lens as it passed through thus coming to a different focus to that of dim moon light.



If it were possible to image the sun and moon at the same time through the same nonlinear lens, both objects would come to focus at the same shorter point. The bright sunlight modifies the path of the dim moonlight passing through at the same time. Scientists can use this principle to change the direction of a dim laser beam passing through a nonlinear medium using a much brighter steering laser. The steering laser changes the local conditions and thus the path of the dimmer beam.



As always, there are many complications to this process. Real world nonlinear materials don't exhibit the ideal behaviour of the lenses here. They have a large linear and much smaller nonlinear component mixed together in their refractive index. Their nonlinear properties also usually have a strong directional dependence and vary with the polarization of the light. However, the basic underlying principle remains exactly the same.

Beams of Matter

Developing a Double Photon Atomic Laser

An optical laser beam consists of a stream of identical photons each with the exact same wavelength and phase. But the physics of lasers isn't restricted to photons; you can also make a laser from a stream of identical atoms.

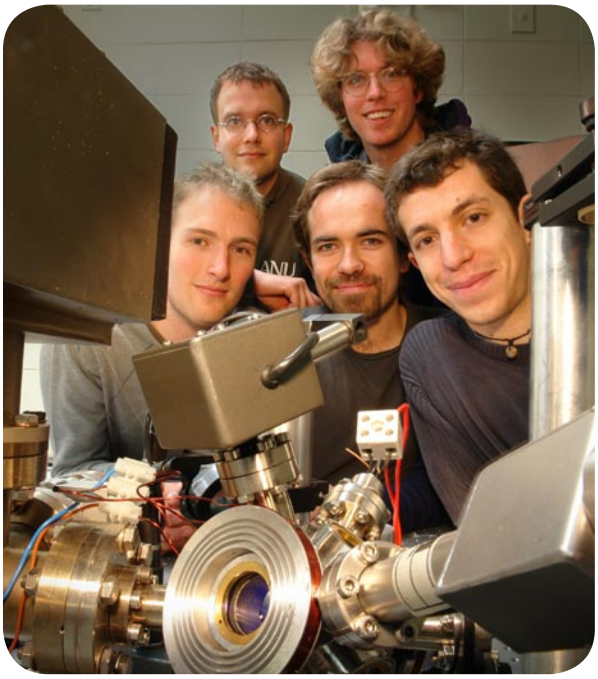
So-called atomic lasers begin with a super-cold cloud of atoms known as a Bose-Einstein Condensate or BEC. The atoms in a BEC are so cold that they take on an entirely new state of matter, each adopting identical quantum properties to the others, just like the individual photons in an optical laser.

In principle, by slowly releasing atoms from a BEC in a steady stream, it's possible to generate an atomic beam with all the coherence properties of an optical laser. As with so many things in science, the practice is a lot more difficult than the principle.

To achieve a BEC in the first place, scientists use optical lasers to slow or cool atoms to almost absolute zero. At such low temperatures the atoms become sensitive to the pull of magnetic fields and it becomes possible to trap them in a carefully designed magnetic cell. As the atoms cool further in the magnetic trap, they begin to condense into a BEC.

To release atoms from the BEC a radio frequency pulse is used to flip their Zeeman state, making them less sensitive to the magnetic trapping field and allowing them to tumble from the trap under gravity. However to make a really good bright atom laser, it's better if they all travel in a single direction with more enthusiasm than a mere tumble.

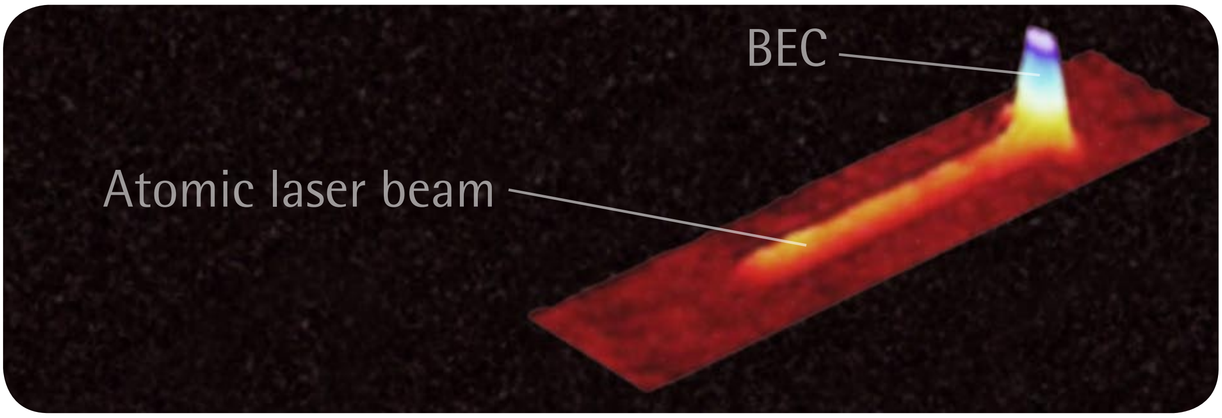
For almost a decade now theorists have been proposing a clever way of achieving atom release from a BEC by using two photons of light to induce a double transition. With the angles, wavelengths and energy all just right, the effect is to flip an atom's Zeeman state thus freeing it from the trap, and also giving it a little kick using the momentum of one of the photons.



Dr Nick Robins and coworkers in the BEC lab

This is very complex to achieve in practice, and until recently had only been done using very short pulses to release little packets of atoms. However, scientists in the Department of Quantum Science recently became the first group in the world to be able to utilise this double photon process to create a continuous steady release of atoms from a BEC forming a bright and highly coherent atomic laser. The work is one of the flagship projects of the ARC Centre of Excellence for Quantum-Atom Optics.

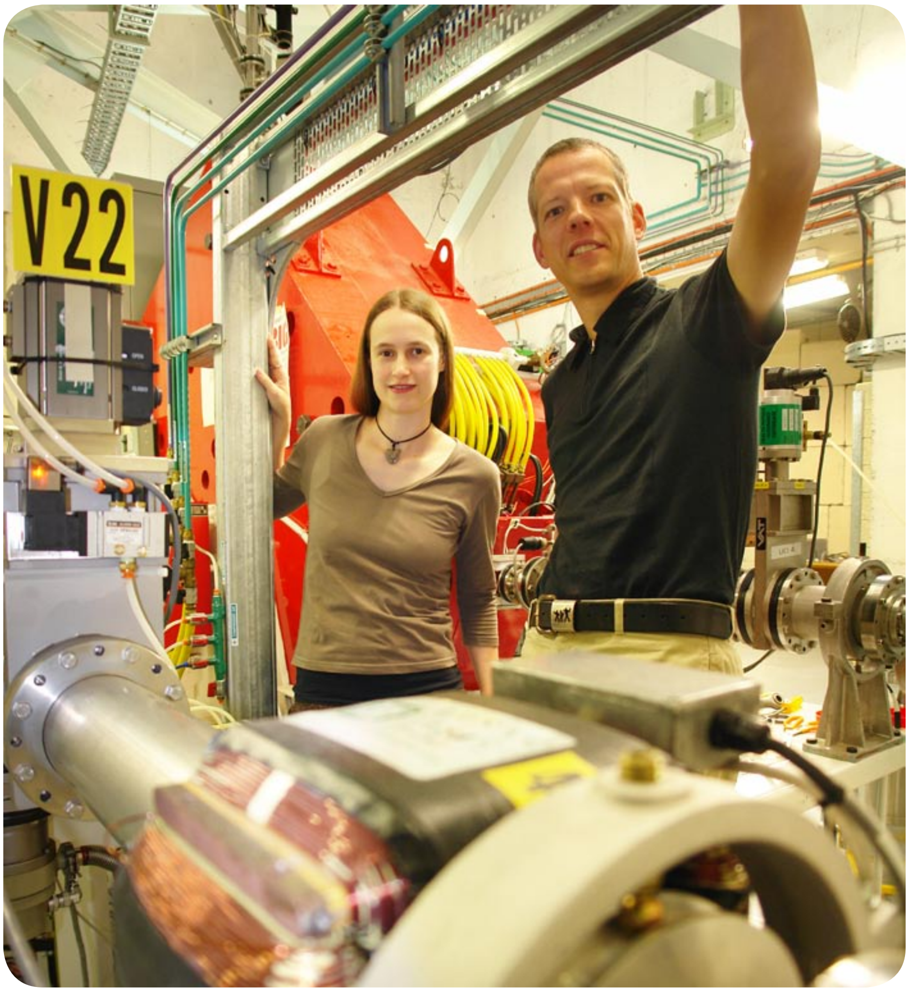
Because of their inherent physical properties, bright atomic lasers offer the potential to revolutionise many sensing applications. For example the theoretical limit to the accuracy of a rotation sensor using an atomic laser is 100,000,000,000 times as high as the same limit for an optical laser based system. Atomic beams also offer major improvements in time keeping which is vital to global positioning systems and to super quiet sensing used in gravity wave detection.



Keeping Track of the Damage

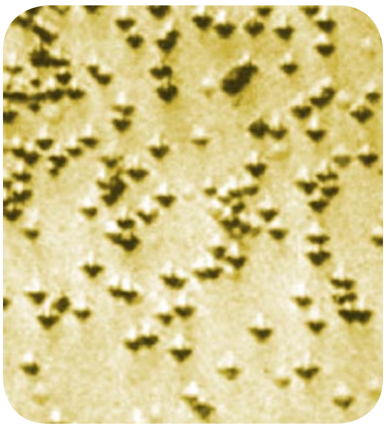
Scientists Resolve Long-Standing Mystery of Ion-Solid Interactions

Silica (silicon dioxide) is one of the most abundant mineral in the earth's crust and consequently is a core component in many rocks. It's quite common for such rocks to also contain natural traces of materials like uranium that undergo slow radioactive decay. This radioactivity produces energetic particles that smash through the surrounding silica creating tracks of localized damage in their wake.



Dr Patrick Kluth and Claudia Schnohr amongst the steering magnets of the 14UD accelerator at The Australian National University

The tracks are too small to see directly but because the damage changes the local structure of the material, such tracks serve as a seed point for certain chemical etches. Suitably etched samples show tiny cone shaped pits in the surface that are visible in a powerful light microscope. Geologists have used this etch pit technique for many years to study the density of tracks. Their interest stems from the fact that knowing the number of tracks in a material and the amount of radioactive material present, you can gain information about the age and thermal history of the rocks. High temperature anneals out the damage so a rock with high uranium content and few pits must have been heated in the relatively recent past.



Conical etch pits seeded at high energy ion damage sites

However, it's not just geologists that have an interest in the interaction of energetic ions with solids. An improved knowledge of such interactions is also pivotal to emerging technologies such as nanofabrication, nuclear waste management, fusion power and long distance space travel. The problem to date has been that remarkably little is known about such ion track damage in solids. The traditional etching technique reveals the number of tracks but removes the tracks themselves, so tells you little about the underlying material science.

This lack of detailed information has created debates and arguments amongst scientists for more than 50 years. However, a research team from The Australian National University led by ARC Australian Research Fellow Dr Patrick Kluth has recently solved the mystery.

Dr Kluth explains, "The exact nature of ion track damage has been very difficult to determine because the tracks are only a few tens of atoms in diameter with often only subtle differences in structure to the surrounding material. A lot of times we are getting localized disorder in a material that is itself highly disordered."

To generate the ion tracks in a controlled manner, the researchers have used Australia's largest and most powerful accelerator, the 14UD at ANU where they bombarded amorphous silica targets with very energetic gold ions.

The world of subatomic particle interactions is very different to our experience of collisions in everyday life. If you're throwing rocks at a tin can the likelihood of you scoring a hit depends on your aim and the size of the can. So long as you aim doesn't falter the likelihood of scoring a hit doesn't change with the speed of the rock. However in the microscopic domain, this common sense no longer holds. The velocity and thus energy of subatomic particles has a large bearing on the likelihood of them hitting each other. This counter intuitive situation arises because the particles aren't really colliding like two solid objects; rather it's their wave functions that are interacting. And wave functions are diffused through local space and time. To keep things convenient, scientists still express the likelihood of two particles colliding in terms of a collision cross section. Bigger cross-section, better chance. The only tricky thing is that this collision cross section changes as the particle energy changes. It's like your tin can getting smaller as the rocks get faster.

For this reason, ions of different energy interact with different components of the target material. Very energetic ions from either natural radioactive decay or the powerful accelerator are very unlikely to collide with the nuclei in the target, as the collision cross section for this interaction is essentially zero at these velocities. This means that the ion loses energy by interaction with the electrons of the host material, not the atoms. The result is a sudden and massive local heating along the ion's trajectory by several thousand degrees. This causes a violent expansion of the silicon dioxide reducing the density along the core of the track and compressing the material in the surrounding cylinder. The area is so localized that the subsequent cooling down is almost instantaneous, preventing the material from returning to its original structure. The net result is a tunnel shaped shock wave frozen in time.

The big breakthrough came with design of high-resolution x-ray scattering experiments to study the structure in the ion tracks. The tracks in the silicon dioxide are amorphous ¬ meaning the crystal lattice structure has no long-range order. However the target silicon dioxide also has an amorphous structure. "It's very hard to see tracks of new disorder in an already disordered material." Dr Kluth explains, "the new measurements, however, enable us to resolve the small density changes in the ion tracks which has not been possible by other means before. We are now confident that we can apply this method to resolve the structure of ion tracks in wide variety of other materials as well."

A crucial aspect for the measurements is that the accelerator-irradiated material differs from naturally occurring silica in one very important way. All the ions from the accelerator were travelling in exactly the same direction when they created tracks. This means that all the damage tracks are parallel. This is vitally important because it makes x-ray analysis viable. To obtain a suitable bright monochromatic x-ray source, the scientists travelled to Chicago to use the Advanced Photon Source synchrotron at Argonne National Laboratory.

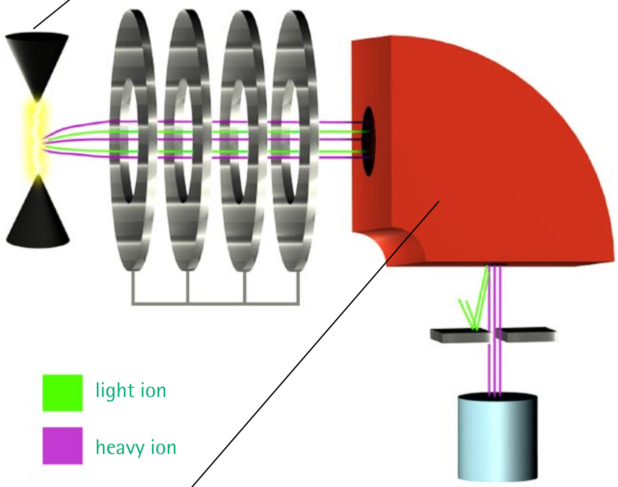
In a natural sample with tracks at random angles, a beam of x-rays is scattered in a different direction by each track resulting in a blurring of the scattering signal. However when the tracks are all parallel each one scatters x-rays in the same direction reinforcing the signal. "What we see in a case like this is a clean superimposition of the signals from each track."

"Apart from solving a long-standing mystery in materials science, these findings have significant potential impact for interplanetary science. In space, equipment is exposed to very high energy cosmic radiation and the response of materials to that is important in designing reliable electric components."

Aerial photo of the Advanced Photon Source at Argonne National Laboratory. Image courtesy of Argonne National Laboratory

A Closer Look at the 14UD Accelerator

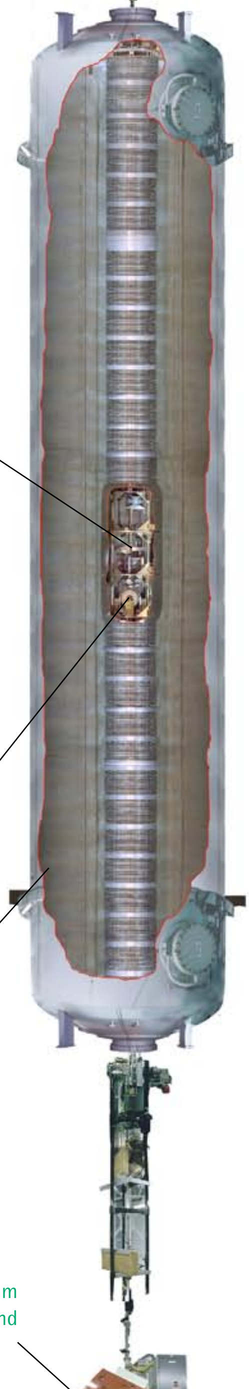
Ions are produced by heating a chosen source material in an electric arc. A series of charged plates with central apertures electrostatically attract and accelerate these ions into the central core of the accelerator which is kept at high vacuum to avoid collisions with air molecules.



The first steering magnet deflects the charged particles according to the Lorentz force equation $F = q (v \times B)$

Where v is the velocity vector B is the magnetic field vector and F is the resulting force vector. From Newton's famous $F = ma$ equation, the acceleration a charged particle (ion in this case) experiences depends on both its mass and the charge it carries. A heavy ion is thus bent less than a light one and a doubly charged ++ ion is deviated more than a singly charged one of the same mass.

In effect this smears out the beam by deflecting the light ions more than the heavy ones. If a slit is placed at the output and the field is correctly adjusted, the magnet assembly can select only ions of a given mass (element) and charge to pass through into the main accelerator tank.



Once they leave the upper steering and mass selection magnet, the negatively charged ions are strongly attracted to the 14 million Volt positive potential at the centre of the accelerator and gain huge speed and energy as they hurtle towards it. Of course if they were simply allowed to pass through and exit the other side they would loose all this energy as they approached the bottom of the tank because the centre electrode's potential would attract them back. To overcome this, a microscopically thin layer of gold foil is placed near the centre electrode. As the ions pass through the foil at great speed many of their outer electrons are stripped off leaving them positively charged. This makes the positive 14 million volts on centre electrode highly repulsive to them and causes them to further accelerate towards the bottom of the tank.

The massive charge at the centre of the accelerator is built up using long rotating chains with links made of alternate insulating and conducting material. These transfer frictional electrostatic charge to the centre of the accelerator tank. The principle is exactly the same as a common Van De Graaff Generator except that in this case, the potential at the accelerator centre reaches 14 million Volts.

Because air breaks down at about 30,000Vcm^{-1} the tank has to be filled with a special insulating gas called Sulphur hexafluoride. At a pressure of six atmospheres this gas has sufficient insulation to prevent arcing between the 14 million Volts of the centre electrodes and the tank wall.

Another steering magnet at the base of the tank changes the ion beam direction to horizontal and enables it to be directed to a variety of targets and experiments.

Rock Cores go Digital

Analysing Rock Cores Takes More Than Fancy X-ray Equipment

Three years ago a group of scientists and major petroleum companies formed a research consortium called Digital Core to explore new ways of analysing oil bearing rock samples. Today, Digital Core leads the world in measuring and modelling porous rock, and the backbone of the consortium is the Computed Tomography Facility that researchers at the Department of Applied Mathematics built from the ground up.

When it comes to tapping an oil or gas reservoir, the fine line between commercial success and failure often comes down to how well you understand the properties of the rocky matrix that contains the oil and gas. How much oil or gas is stored in the rock? How easily can that oil and gas be extracted? Is it possible to flush the oil and gas out by injecting some fluid into the porous rock (and if so, at what rate)? These are all important questions that can take enormous sums of money and large amounts of time to answer by studying rock cores extracted from potential reservoir sites.

Professor Mark Knackstedt, one of Digital Core's founders and currently head of Applied Maths, has spent many years attempting to mathematically model complex materials and specifically oil-bearing rock. The work began in the early 1990's by building three dimensional models of rock structures using information from two dimensional thin sections, a laborious and painstaking job. In 1998, while visiting the United States, he was shown three-dimensional tomographic images of road samples and became excited by the opportunity to directly image 3D structure in detail. Tomography is the process of taking many X-ray projections of a sample at different angles and stitching them together with software to create a three dimensional image of the sample. It's often referred to as CT or computed tomography.

"This was pretty impressive stuff," says Professor Knackstedt. "I returned to Australia proposing that we do some tomographic imaging of rock ourselves; so, a group of us at Applied Maths including Stephen Hyde, Tim Senden and many others, put together a linkage proposal to build our own facility.

"The proposal got up and we then had to decide whether to buy an off-the-shelf system or build our own. Having several experimentalists (such as Arthur Sakellariou, Tim Sawkins and Tim Senden) in the department with experience at developing a variety of equipment we felt we could design something that was much better than anything we could purchase, so we set about building our own CT unit. Of course, there were many problems to solve in the process and it ended up taking around two and half years to build; much of this time was spent at a white board discussing the design of the facility.

Professor Mark Knackstedt holding a rock core. Digital Core has revolutionised our capacity to analyse complex rock structures

But what Applied Maths came up with was one of the most powerful and flexible micro X-ray CT facilities in the world; a unit so impressive that similar units have been made and sold to companies around the world. It's described as 'micro' because it's primarily designed to scan objects with length scales ranging from microns through to millimetres.

However, the researchers quickly realised that powerful hardware was only half the story. When you're scanning complex rock structures (over multiple length scales simultaneously) you're generating vast data sets; data sets so huge that you literally need a supercomputer to work with, manipulate and analyse them.

"In many ways it was fortunate that it took two and half years to build the physical equipment," comments Professor Knackstedt. "That's because it took a long time to write software and to build the computational infrastructure to handle the sort of data that was being generated. Indeed, handling the enormous datasets is one of the biggest problems with tomography.

"In a sense, the jewel in crown of Digital Core is the work done by the computational people, particularly Adrian Sheppard, Rob Sok, Holger Averdunk who initiated the work. This group has expanded considerably and now includes over 12 postdoctoral and more senior fellows building a broad range of software tools to handle and work with this data in a timely fashion. And that's something that we believe is missing from almost every other CT facility in the world working in this area.

"About three years ago we knew that we had something that was quite unique globally, and we were getting extremely positive feedback from the petroleum sector. The oil and gas industry spends vast quantities on extracting rock cores from reservoirs and traditional methods of analysis take months to years. Our tomographic scanning and digital analysis only takes days and provides much more detailed information than was previously available.

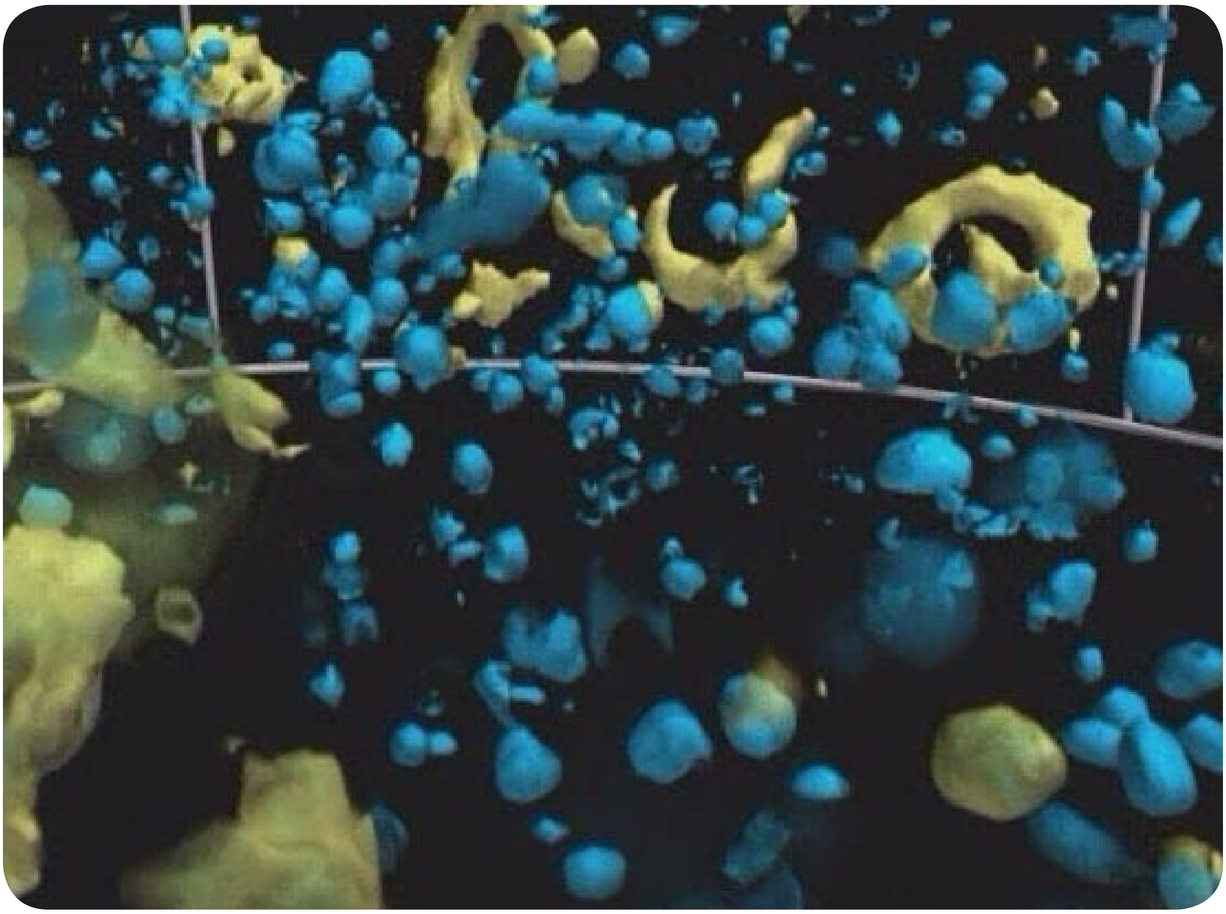
"And so we formed Digital Core, a consortium consisting of a group from here at Applied Maths, a group of petroleum engineers from the University of NSW, and money and resources from 14 of the world's major oil and gas companies."

And Digital Core has proved an enormous success with oil companies obtaining precious intelligence on their cores while the university has received funding to refine and extend the tomographic analysis of rock and a range of other complex materials.

"Our research has extended way beyond just oil-bearing rock," observes Professor Knackstedt. "For example, some of the methods we have developed on analysing porous rock has extended to research on bones and osteoporosis. We're also developing applications that will be valuable to tissue engineering, foamed materials, fossils and a range of manufacturing materials."

Digital Core partners are now considering how the consortium might develop in the coming years.

"The value of Digital Core's expertise has now been conclusively demonstrated and the demand for our expertise is only growing," says Professor Knackstedt. "It'll be interesting to see where things go in the years to come.



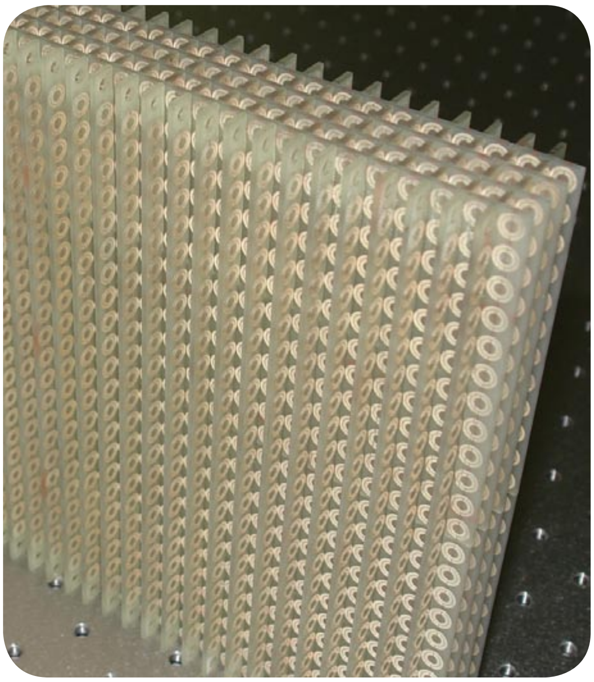
Oil and water suspended in sandstone - image Digital Core Lab

Cloak of Invisibility?

Exploring the Properties of Materials with Negative Refractive Index

Have you ever wondered why completely transparent objects like wine glasses are so easy to see when windows made of the exact same material are almost invisible? The answer lies in a property of materials known as refractive index – their ability to bend light. Materials like glass have a high refractive index and therefore bend light as it enters or leaves them. Light hitting a flat window is all deviated in the same way, so the image remains undisturbed and consequently, the window is almost invisible. However the curves of a wine glass mean that light strikes the glass at different angles in some places than others and is therefore bent differently. In this case what we see is a warping of the surrounding image, which our brains conceptualise as a physical object – the glass.

But why do materials refract light in the first place? The refractive index of a material is created by a combination of the electric permittivity and magnetic permeability, which are themselves, dictated by the atomic structure and composition. In plain English, this means that a photon of light, which is made up of oscillating electric and magnetic fields, is perturbed by the rows of tiny electric and magnetic dipoles formed by the individual atoms making up the glass.



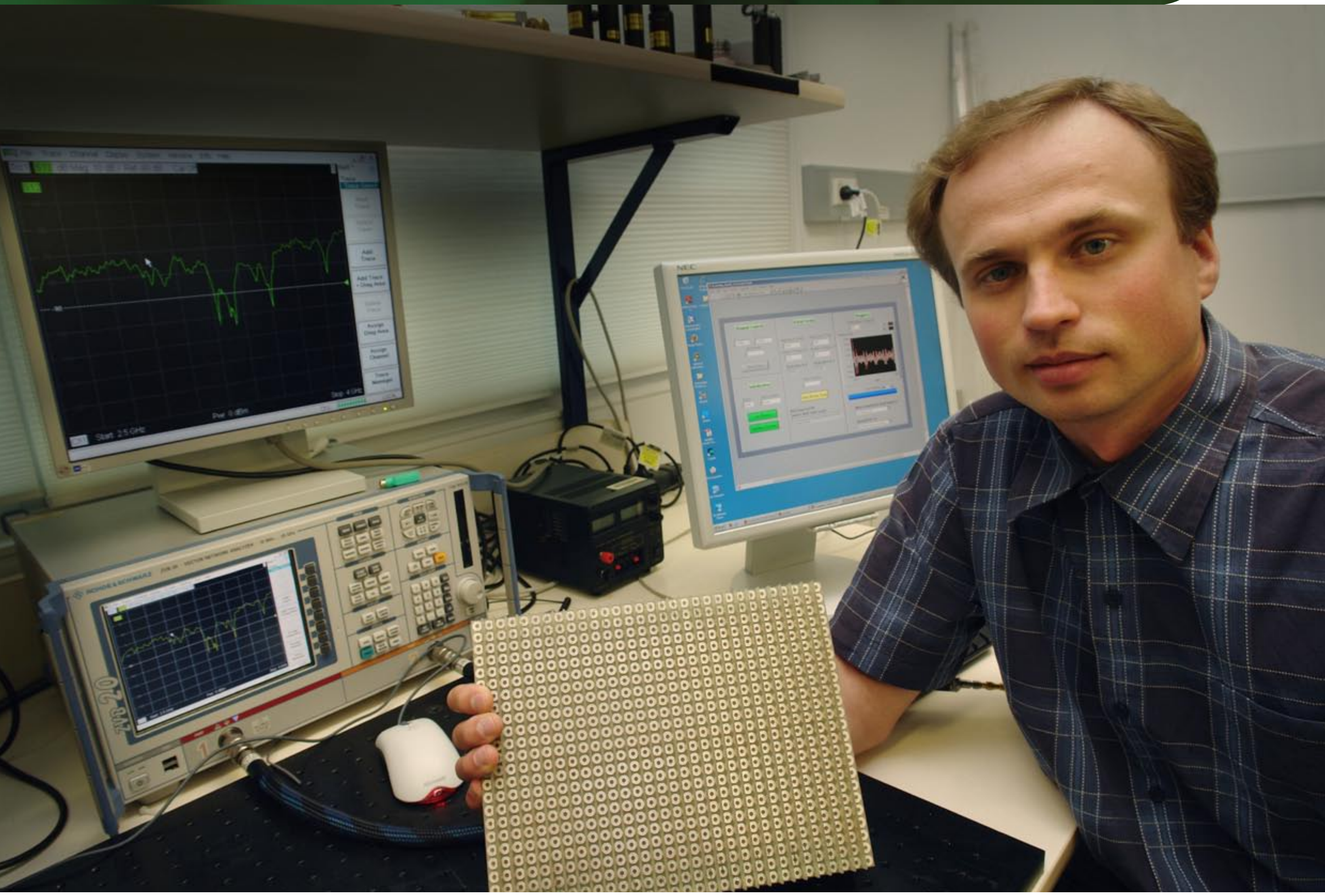
Close up of a metamaterial designed to operate at microwave wavelengths

Refraction is a key factor in rendering transparent objects visible

The mathematical analysis of refraction at the atomic scale is highly complex but the important end result is that light changes direction when entering and leaving refractive media. All materials found in nature have positive permittivity and positive permeability leading to positive refractive indices. There are however a class of artificially created substances called left handed metamaterials, that can be engineered to exhibit negative refraction.

Dr Ilya Shadrivov has spent many years with the Nonlinear Physics Centre investigating these exotic negatively refracting matamaterials, initially developing sophisticated theoretical models then later testing their predictions in the laboratory using real materials. The process of producing crystals with such negative refracting properties in visible light would be a highly complex and expensive exercise in nanotechnology and would not offer the control and flexibility required to work on developmental systems. So instead, the researchers use large-scale arrays of dielectrics such as fibreglass containing lattices of electronic components. Instead of visible light, the scientists irradiate these test arrays with microwaves that have far longer wavelength - in keeping with the scale of the lattice. "In optically transparent materials such as glass, the individual atoms are in effect tiny row of electric dipoles interacting with passing waves. In the large-scale lattices used in our research, the diodes serve the same purpose. What's more, if we use variable capacitance diodes on wire loops whose electrical properties change with field strength, we can induce non-linear behaviour." Dr Shadrivov explains.

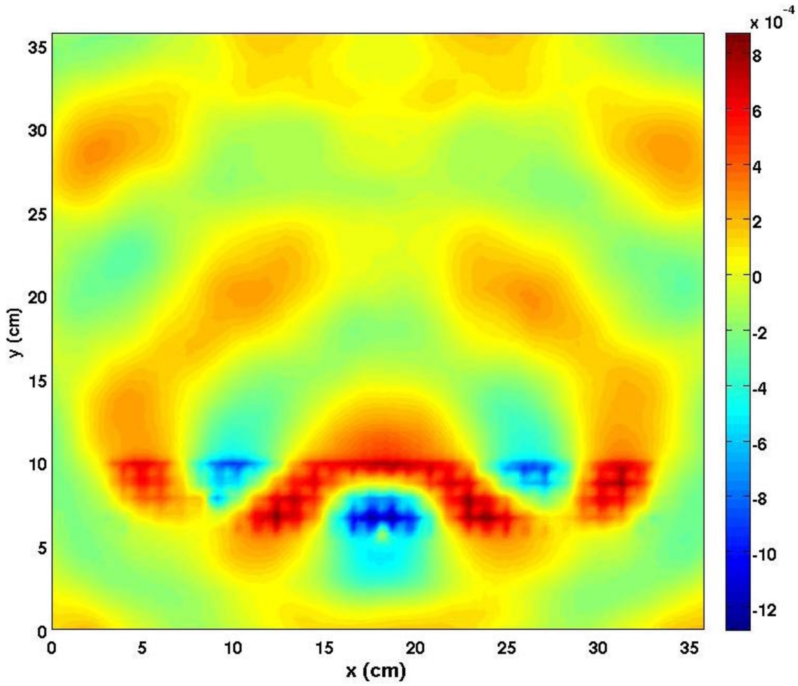
"The use of these large-scale diode arrays gives us the flexibility we need to test and further develop our models, yet is on a scale easily constructed by humans. The electromagnetic microwaves are longer and the lattice is bigger, but the physics and mathematics is exactly the same as for visible light."



Dr Ilya Shadrivov with a nonlinear metamaterial, other members of the group are Dr. David Powell, Mr. Steven Morrison, Professor Yuri Kivshar

The ANU group has for years been a world leader in the theoretical treatment of nonlinear matamaterials and has recently become one of the first groups in the world to practically demonstrate such behaviour in the laboratory.

At the moment these exotic nonlinear matamaterials represent the forefront of materials physics. However it's quite possible that within a few years they will lead to the realization of technology straight from the pages of science fiction. For example, an appropriately used shell of the right negatively refractive metamaterial may be able to bend light or radar around an object and redirect it to its original path on the other side. Such a device would render the object inside, completely invisible.



Laboratory measurement of an electromagnetic wave scattering on a nonlinear metamaterial. The large scale of the microwave based materials enables researchers to more easily measure the spatial behaviour of electromagnetic radiation as it interacts with them.

Nanowool

Exploring the Potential of a Novel Form of Silicon

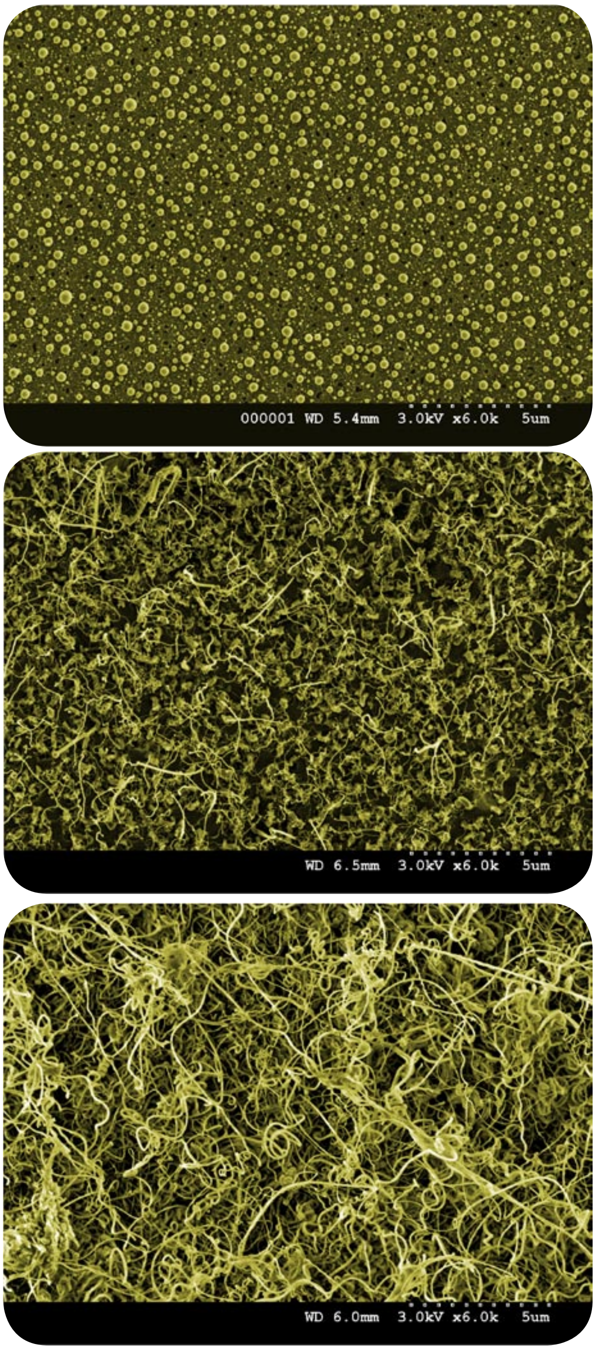
There have been many instances in history where prominent scientists have claimed to know pretty much all there is to know about a particular topic apart from sorting out a few minor details. What has almost invariably happened in such cases is that those details have proved to be vitally important and when investigated, they have revolutionized our view of the world. To a good scientist an unresolved detail should never be swept under the carpet, as it may be a gem in disguise.

It was during the course of investigating just such a troublesome detail in thermal processing of silicon wafers that a group of ANU researchers began to uncover the underlying science of a process that may have profound applications in nanoscale biosensors. Professor Rob Elliman and his team noticed that some of the silicon wafer chips they were annealing under high temperature inert gas had white discolouration around the edges. More surprising still, if the wafer chips had a metal film on their surface, the white material covered the entire sample when annealed under certain conditions.

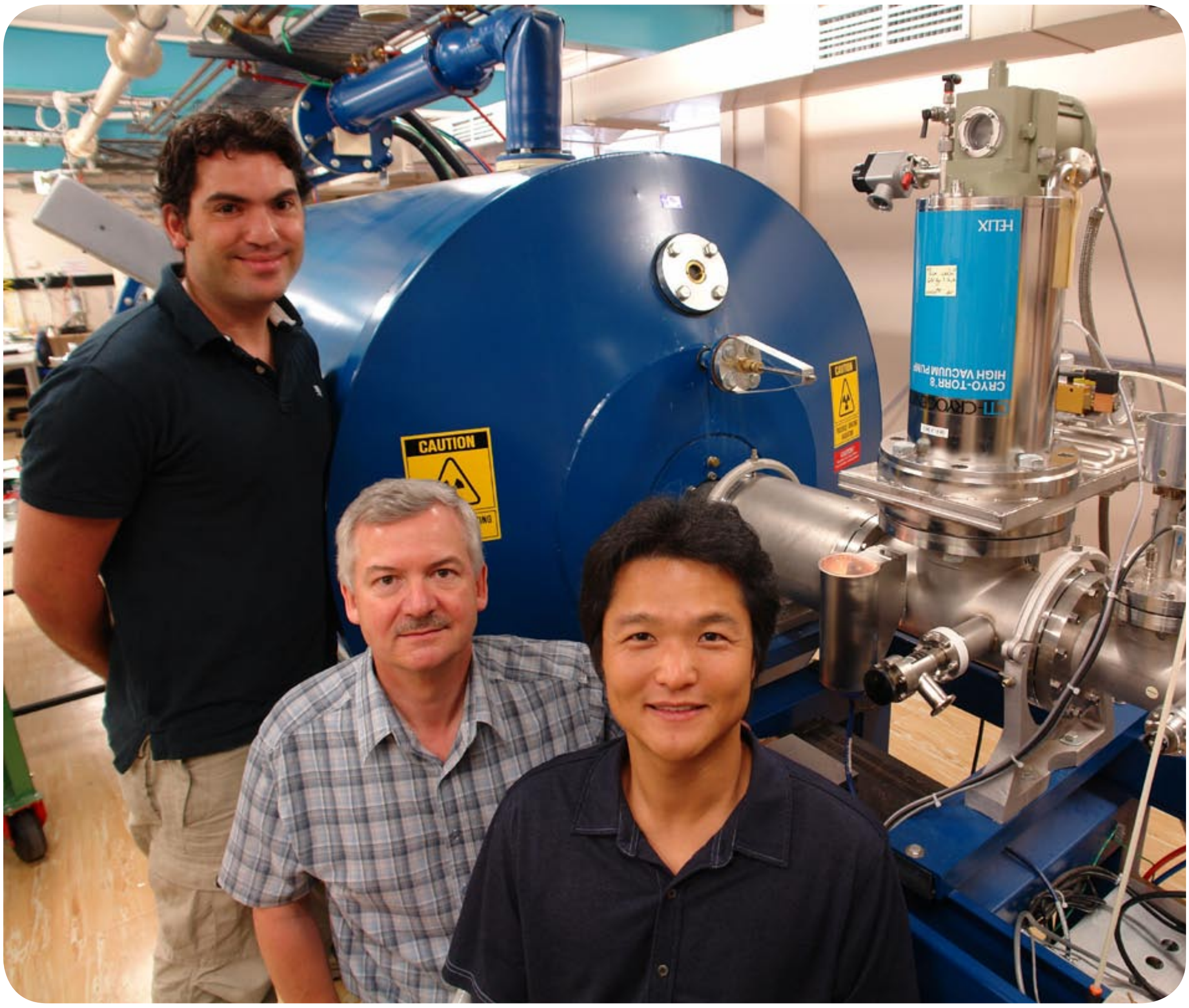
Thermal processing of silicon in inert atmospheres is a common procedure in the semiconductor industry but generally; the temperatures are not nearly high enough to create this surface discolouration. As a result only a handful of researchers had come across this in the past and the underlying science had never been completely understood. The team were intrigued and decided to investigate.

Initial analysis revealed that the material was silica dioxide (SiO_2) which was surprising because nominally, there was no oxygen in the system. Even more surprises came when the mystery material was examined under the electron microscope. It turns out that the SiO_2 was in the form of nano-wires that were an incredible 2mm long. That would be the equivalent of a head of human hair stretching 5km. The team set about trying to understand the growth mechanism of this nanostructure by subtly varying the growth conditions, introducing slabs of different source material near the wafer and even using different types of furnace tube. It's very difficult to isolate factors in a high temperature system that can be affected by a couple of parts per million of common elements.

Extensive analysis revealed that the oxygen in the SiO_2 nanowires was being provided by the few parts per million residual impurities present in the inert gas used to purge the furnace tube. Under high oxygen concentrations and at temperatures above about 1000°C silicon will form a thick coating of solid SiO_2. However, at very low partial pressures of oxygen, volatile SiO forms on the surface of the wafer and is absorbed by the metal particles on the surface at a great rate. The silicon/metal eutectic then transports the SiO to growth sites on the wires. Under some conditions, the tiny metal blobs sit at the tip of each growing wire. If the parameters are varied, the blobs remain on the surface, the wires extruding from them like hairs from a mole. This difference could be vital



Stages in the growth of nanowool from eutectic "blobs" to fully extended wires



Dr Avi Shalav, Professor Rob Elliman and Tae-Hyun Kim with a high energy ion implanter

in potential practical applications as it affects the adhesion of the layer on the substrate wafer.

Although the science of the nano-wool production process was interesting in itself, the researchers also wanted to develop a practical application for the novel material. During the course of their other work on silicon, Professor Elliman's team use many laboratory diagnostic techniques, including photoluminescence - the re-emitted light from a crystal after excitation by a laser pulse. The spectrum and lifetime of photoluminescence can reveal a great deal about the properties of a material. This set the team thinking about what might happen if the wool were excited by laser pulses. Normally one would see the properties of the bulk SiO_2 but the long fine wires might theoretically be expected to add an extra dimension to this.

When light is totally internally reflected within a high refractive index medium - such as it is when it bounces down an optical fibre or SiO2 nanowire, the sinusoidal electromagnetic oscillations of the photons extend slightly beyond the physical medium. This exponentially decaying external field is called the evanescent wave and exists because the electric and magnetic fields of the photon cannot be discontinuous at a boundary. The practical upshot of this is that if the properties of the environment the fibre or nanowire sits in affects the light propagating within it. Thus if a mat of suitably prepared nanowool is excited by a laser pulse, the re-emitted photoluminescence signal from the fibres will have a differing intensity and life-time if the air between the fibres contains certain chemicals. The researchers believe that this may make suitably coated nanowool a great candidate for a solid-state sensor for anything from alcohol to biologically important molecules.

It's still early days for nanowool sensors and the researchers are cautious about making grand predictions, but at this point the possibilities do seem quite exciting.

Fusion Power

Making Sense of High Temperature Plasma Confinement Data

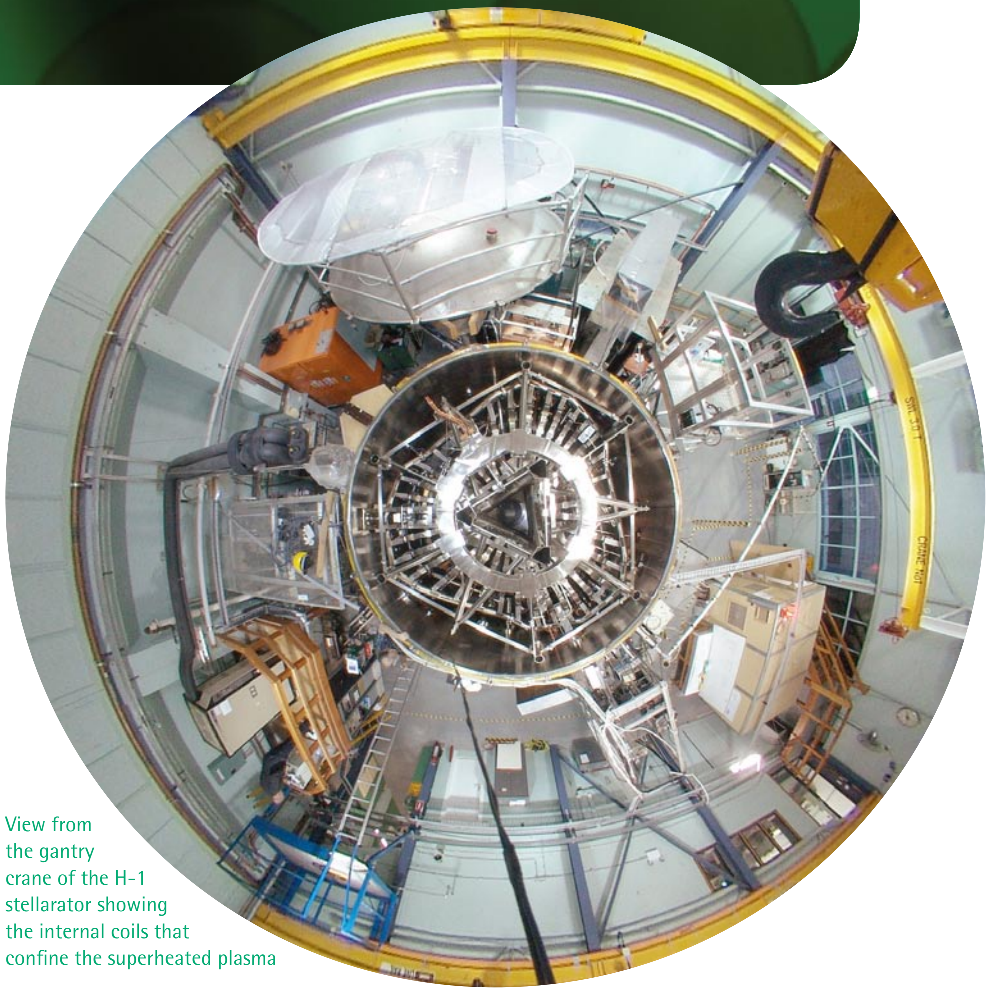
Fusion power offers the promise of generating massive amounts of energy with essentially zero greenhouse gas emissions and few of the safety issues of conventional nuclear energy. But although huge progress has been made in the past 50 years, we are only just beginning to reach the elusive "burning plasma" condition, where output power of the confined products exceeds the input power required to heat the fuel.

The next step international fusion experiment ITER, is now under construction in France and is one of the world's largest science experiments. ITER plasma temperatures will be exceed 100 million degrees C, with a plasma volume comparable to an Olympic swimming pool. The construction of ITER is only possible because physicists are able to model the behaviour of plasmas sufficiently well to enable engineers to construct a machine on this scale with confidence. However, there is still much work to be done before we have a complete understanding of the theory underlying plasma confinement.

The behaviour of all fluids is notoriously difficult to model. Even a simple fluid such as water exhibits a myriad of twists and turns as it flows from a tap. Plasma circulating within the magnetic confinement of a fusion reactor is far more complex because it has massive temperature gradients and is composed of charged particles that repel and attract each other as they circulate. This constantly moving charge also generates its own magnetic field which in turn, perturbs the flow of the plasma and disrupts the magnetic field used to confine it.

Australia's contribution to the worldwide effort to develop fusion power centres on international collaborations, many of which harness the H1 National Plasma Fusion Research Facility at ANU. H-1 is a stellarator plasma confinement facility not designed to actually achieve fusion, but to conduct experiments on large scale confined plasmas. The relatively easy reconfigurability of the magnetic fields within H-1 makes it a particularly good tool for the development of diagnostic instruments to monitor the behaviour of confined plasma. However, Interpreting the gigabytes of data from the temperature, pressure and current sensors inside the plasma is a daunting task. Even more challenging is the globally

Drs Greg von Nessi, Matthew Hole, Boyd Blackwell and Professors John Howard and Bob Dewar with the H-1 stellarator

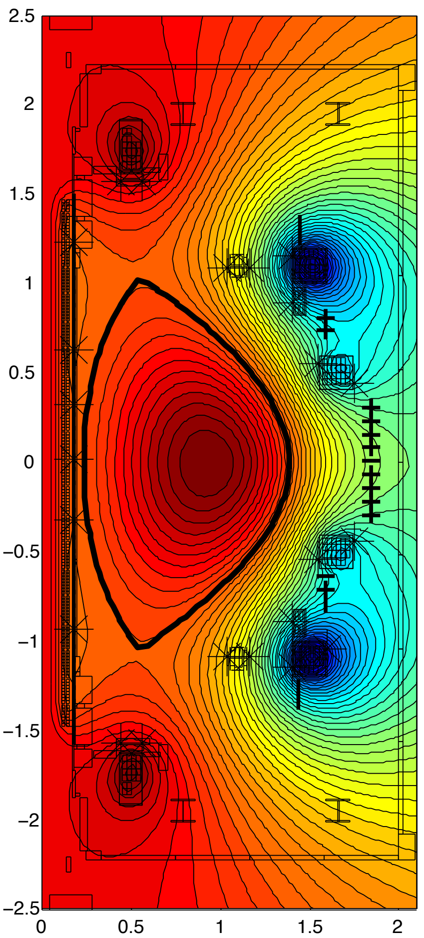


View from the gantry crane of the H-1 stellarator showing the internal coils that confine the superheated plasma

consistent merging of this information into a cohesive picture that reflects the actual physics of a plasma confined in such extreme conditions.

Drs Matthew Hole and Greg von Nessi are part of the ANU Plasma Theory and Modelling group, who with collaborators (see photo) in the Plasma Research Laboratory are focussing on interpreting data from the many sensors on H-1 and compiling a picture of the underlying physics.

"The different diagnostics on H1 are a lot like our own five senses," Dr von Nessi says. "Data comes in from sight, sound smell, and often something we're experiencing influences more than one sense. In fact it's the interaction between senses that often enables us to make sense of what's in front of us. This is exactly the same situation with a confined plasma. We have hundreds of variables and only a few measurements we can make. But if we can make better use of the interdependency of those measurements, then we can generate a far clearer picture of what's going on."



Poloidal flux surfaces of a plasma discharge in the MAST experiment

The way our brains work is hugely sophisticated and complex but because we're part of the system we usually just take it for granted. But how do you go about building a rigorous mathematical model that in a sense, does the same thing?

Their model is compiled using a mathematical technique called Bayesian inference. The basic principle is that you begin with a scientific belief or expectation, add the observed data and then modify the extent of that belief to generate the next expectation. In effect as more and more data is added to the model the accurate predictions become reinforced and the inaccurate ones rejected. "It's a lot like the way we learn things," Dr von Nessi says, "We generate ideas based on experience then reinforce or reject them as more data comes in."

"We wanted to ground our approach to modelling the behaviour of plasmas in sound physical theory such as Maxwell's equations, but not to incorporate untested assumptions that might bias the outcome."

The beauty of this approach is that you don't have to deal directly with the hugely complex interdependencies within the data but those interdependencies are automatically incorporated into the model.

"By not building so many assumptions into the initial model, it's possible to compare what's going on in the data to various aspects of the physics" Dr Hole explains, "We can then use real data to give credence to, or reject proposed physical descriptions of the plasma."

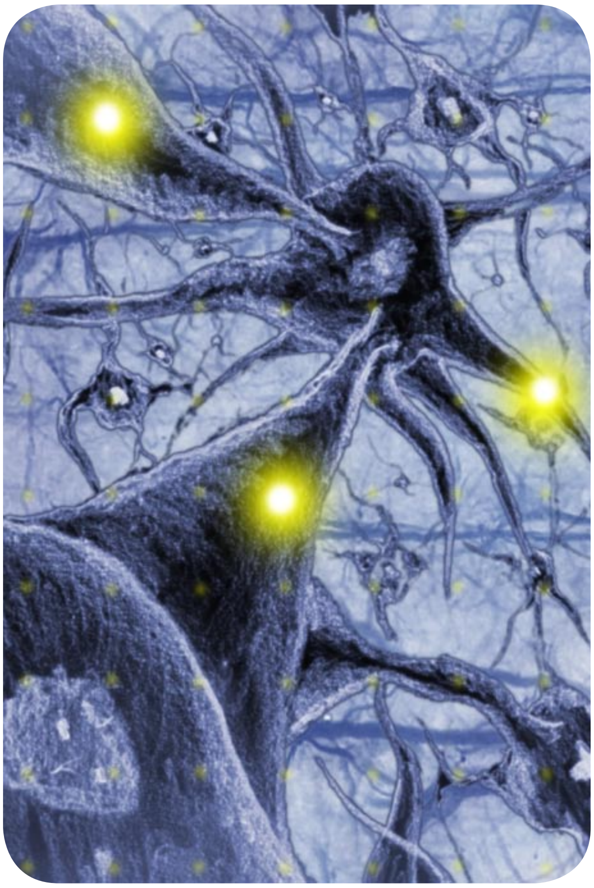
The Bayesian inference techniques being developed for this project are currently being used to help understand the theory of force balance on the higher temperature Mega Ampere Spherical tokamak, at UKAEA Fusion in the UK. But the underlying mathematics can be applied to many different complex systems and may even find applications in areas as diverse as climate change and global financial markets.

The Holographic Neurone

When Physics and Biology Combine

For some time neuroscientists have been using microscopic electrodes to excite nerve cells in order to study their response to various stimulation patterns and to unravel the secrets of how nerves process information. However, inserting an electrode into a dendrite only a few µm thick is a very difficult task. Doubly so if you require multiple points to be stimulated at the same time. This approach is also slow and painstaking so you can't really select and excite a sequence of contact points as anywhere near as fast as it happens in living neural networks.

This reliance on electrodes has posed some limitations on the types of experiments neurobiologists have been able to conduct. However, two neurobiologists, Dr. Christian Stricker and Prof. Steve Redman of the John Curtin School of Medical Research, have recently achieved a breakthrough in this area in a collaborative project with physicists at the ANU Department of Quantum Science.



The Holographic Neurone Stimulator uses localised light pulses to stimulate points on living neurones in real time

"We were looking for a system that could generate real time images of living neurones in three spatial dimensions and then stimulate those neurones at several specific points." Dr Stricker explains. "So we approached physicists Professor Hans Bachor and Dr. Vincent Daria to explore what we might be able to achieve collaboratively." As often happens with collaborations, experts from diverse fields were able to pool their expertise and create a system that none of them could have built individually. The result was a new tool in neuroscience which the team have christened the Holographic Neuron Stimulator.

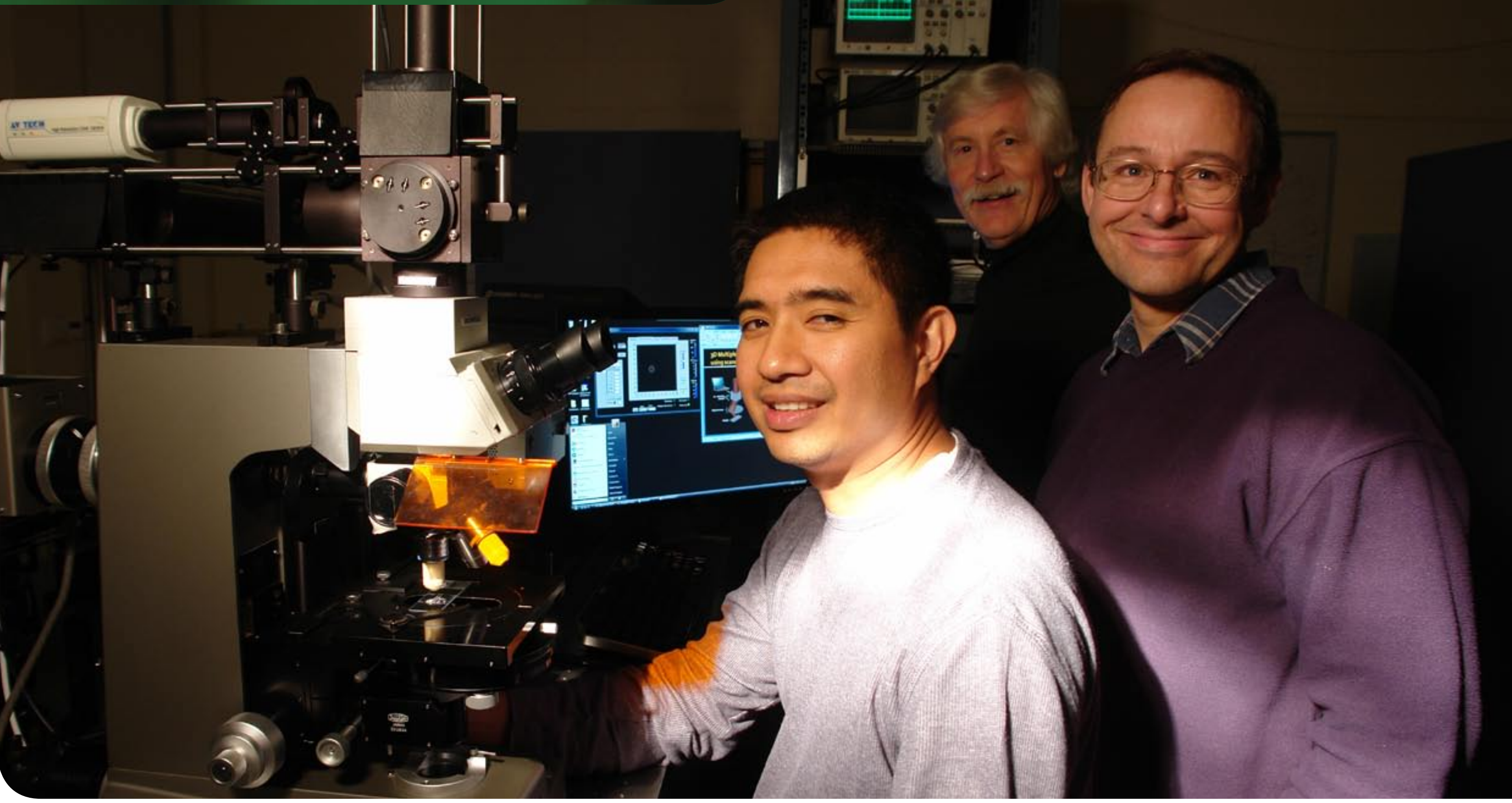
The Holographic Neuron Stimulator works by immersing a sample of living neurones in a solution containing neurotransmitters - a class of molecules that stimulate neuronal firing. Of course if the cells were simply bathed in active neurotransmitters they would fire constantly. So scientists have adapted a "caged" neurotransmitter molecule such that it only becomes active (or "uncaged") in the presence of a strong light field.

In order for the system to work effectively, the triggering light has to be highly localised at selected points in space. The team decided that the best way to achieve this was to use a holographic projection technique.

A normal photographic hologram is a combination of dense and transparent regions in a photographic emulsion that don't outwardly look like anything recognisable. But when illuminated by a broad plane coherent wave, such as that produced by an expanded laser beam, the dense and transparent regions in the hologram project an interference pattern that mimics an object in 3 dimensional space. In conventional holography, the hologram is recorded on a photographic plate using the reverse process – laser illumination of a real object and interference with a second beam. Although many holograms are recorded in this photographic way, it's quite possible to calculate the holographic pattern of an object using optical theory alone. Such pre-calculated holographic patterns are commonly called Computer Generated Holograms (CGH). A programmable electronic light modulator can be encoded with such a CGH, and project a complex three dimensional light pattern from a single laser.

The projected light pattern from the hologram can be in the form of tiny spots of light, which could in principle be used to create bright spots within sections of neural tissue. If that tissue were surrounded by an inactive "caged" neurotransmitter solution, the holographically projected bright spots would release (or uncage) the transmitters at various points in the sample. If those points were made to correspond with the location of a nerve cell membrane, the result would be to stimulate the cell and potentially initiate a nerve impulse.

Stimulator



Dr. Vincent Daria, Dr. Christian Stricker and Professor Hans Bachor with the prototype Holographic Neurone Stimulator

And this is precisely what the Holographic Neuron Stimulator does. Using a programmable hologram to alter the shape of the laser beam and a powerful computer, the machine creates a series of patterns of spots in precisely determined locations for stimulating various sections in a neuron. This is more versatile than using a simple mask or lens. Another advantage is that it can be changed in real time allowing the light spots to be switched and moved every few milliseconds. In this way scientists can stimulate several points on the same neurone either simultaneously or in a set temporal sequence.

A significant challenge with any optical neurone stimulating system is correlating your light spots with features on the actual neurones in the sample. The Holographic Neuron Stimulator achieves this by using the same holographic technique to create a special kind of microscope known as multi-photon fluorescence microscope or MFM.

An MFM works by using a femtosecond-pulse laser to excite natural molecules in the sample into fluorescence. The simplest kind of fluorescence is when a molecule absorbs a highly energetic photon and re-emits a less energetic one. This is commonly seen when things glow under ultraviolet light. This isn't very useful in microscopy as it would cause the entire sample to absorb light and glow at once. So the fluorescence event employed by a MFM is the absorption of two or more low-energy infrared photons to excite one molecule, which then emits in the visible spectrum. Because of quantum rules, in order to raise the energy in two jumps, both photons must be absorbed by the molecule at exactly the same time. Hence, to increase the probability of simultaneous multi-photon absorption, the density of photons at an instant of time needs to be very high, which can only be achieved in a strongly focussed pulsed-laser with pulse-width in the order of several femtoseconds (10^{-15} s.)

Prior to using the Holographic Neuron stimulator to excite impulses, a 3D image of the neuron sample is created by switching the system to MFM mode. By raster scanning the femtosecond-pulse laser beam across the sample very quickly, a beautiful crisp three dimensional image of the neuron is generated. Once the 3D image of the neuron is acquired, the hologram for projecting the appropriate light spot pattern is calculated and encoded on the programmable hologram.

To a neuroscientist trying to understand how billions of individual neurones integrate together to create complex structures like the human brain, this new technique offers a very exciting opportunity to do new science. "The great thing about this set up is that you can generate an image of a living neurone in situ, identify points that you wish to stimulate, then switch to stimulate mode and directly hit those points in any sequence you like. " Dr Stricker says. "In neuroscience we are always looking to push the boundaries and this should really help us do so." He is looking forward to the first trial runs of the stimulator.

Lollipops in Nanospace

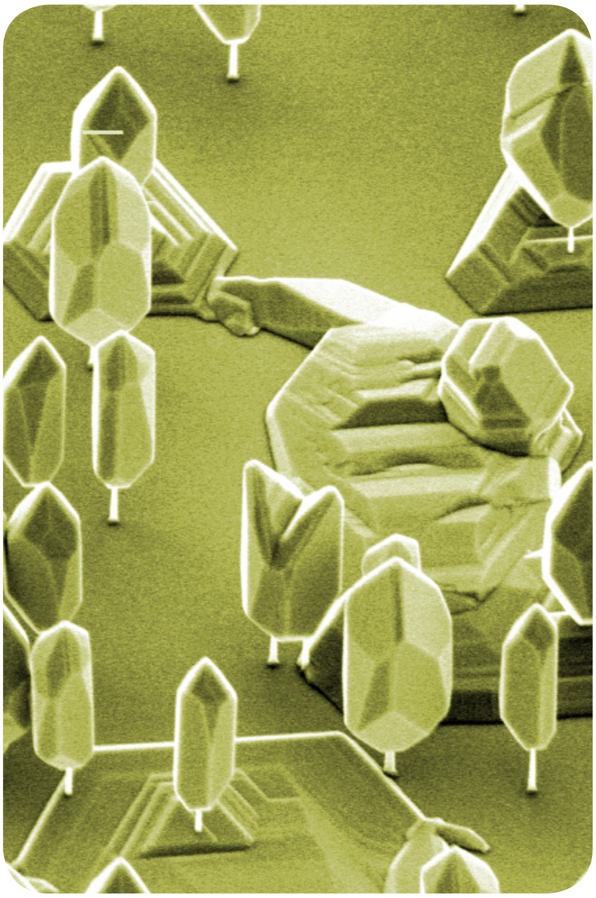
Creating Exotic Nanostructures in Gallium Arsenide

The alien scene pictured below shows crystals of pure gallium antimonide sitting on top of spindly stalks of gallium arsenide. The stalks are around 30 nm in diameter and the formations were grown by Dr Michael Gao, a postdoctoral fellow in the Department of Electronic Materials Engineering (RSPSE). They represent new efforts to work with the semiconductor gallium antimonide.

Dr Michael Gao

"There's a lot of interest in working with gallium antimonide," says Dr Gao. "It possesses a band gap that makes it an excellent material for many optoelectronic devices such as lasers and infrared detectors and LEDs. Unfortunately it's very expensive and it's difficult to deposit on other more commonly used semiconductor wafers like gallium arsenide.

"That's because gallium antimonide has a larger lattice constant than gallium arsenide. When it crystallises on top of a wafer of gallium arsenide, large amounts of tension develop in the crystal structure of the gallium antimonide as the two crystal structures attempt to match. This tension prevents the gallium antimonide from forming smooth layers or growing into usable shapes."



"However, we have discovered that if you grow gallium antimonide on top of a nanowire of gallium arsenide that the gallium antimonide crystal can grow without large amounts of tension. We believe this is because the nanowirebase from which the gallium antimonide is growing is small enough not to impose its crystal structure on the newly forming crystal."

Dr Gao's work is part of the research of Professor Chennupati Jagadish's Semiconductor Optoelectronics and Nanotechnology Group on nanowires. The Group has been growing nanowires by placing nanoparticles of gold onto semiconductor wafers of gallium arsenide. The sample is then placed in their MOCVD (Metal Organic Chemical Vapour Deposition) reactor and heated causing the gold nanoparticles to melt. Gallium and arsenic atoms are then passed over the sample in the form of a vapour and a nanowire of pure gallium arsenide starts to grow under the gold droplet.

Having become confident in their capacity to grow simple gallium arsenide nanowires the researchers are now exploring a variety of ways of modifying the wires, including the incorporation of different elements.

The hetero-nanowires that Dr Gao has been growing have gallium antimonide on top of gallium arsenide. Because the gallium antimonide has the larger lattice constant it grows out rather than tapering in. In so doing, it forms nanoscale lollipops, popsicles or match heads depending on the particular growth treatment being applied.

Clearly Infrared

How the High Infrared Transparency of Chalcogenide Glass Promises Technological Innovation

Dr Rong Ping Wang loading a target into the chamber for laser deposition

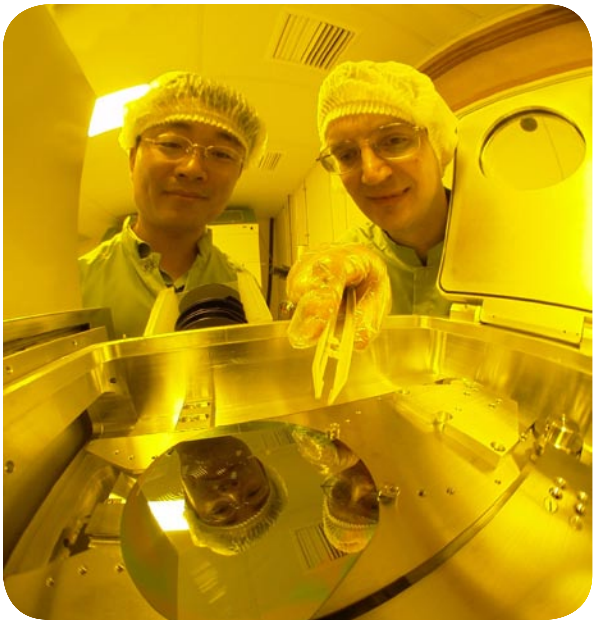
ANU researchers are setting new world records in processing a range of glass materials used to manipulate infrared light. Their results set the scene for a revolution in infrared technology that promises increased internet speed and much more besides.

Infrared light is that region of the electromagnetic spectrum that extends from the red end of visible light out to what we feel as radiant heat. It's a range of light wavelengths at the centre of many amazing applications that include remotely detecting explosives, chemicals and biological agents; dramatically speeding up internet communications; and even helping us detect earth-like planets in distant solar systems.

But working with infrared light has always been a challenge because, unlike other wavelengths in the visible spectrum, it doesn't transmit well through standard glass. However, there is a range of materials known as chalcogenide (pronounced chal – koj – enide) glasses that are excellent performers when it comes to the transmission of infrared light. If we could build tunable infrared sources and optical chips out of chalcogenide glass it would open up a new world of infrared usage. The reason it hasn't happened yet is because chalcogenide glass is devilishly difficult to work with.

"Chalcogenide glasses are basically alloys that contain one of the chalcogon elements on the periodic table," says Dr Steve Madden from the Laser Physics Centre. "These include sulphur, selenium or tellurium, and they're typically alloyed with elements like germanium, arsenic, gallium, antimony and silicon. These glasses are already used in thermal infrared night vision systems but up till now it's been a major challenge to take them the next step and use them in thin films as part of optical chips and waveguides.

Clearly infrared continued.....



Dr Duk Choi and Dr Steve Madden working with a plasma etcher

"The problems are two fold – producing a film of chalcogenide material with minimal defects and of the desired composition, and then processing it without introducing imperfections that will destroy its ability to transmit and manipulate infrared light."

And researchers at the Laser Physics Centre have made significant advances in both areas. First, in order to create superior quality chalcogenide films they employ an ultrafast pulsed laser to ablate chalcogenide glass targets. Atoms dislodged from the target are then deposited as a thin film.

"The material being deposited is quite literally ripped apart at the atomic level by a laser pulse about a millionth of a millionth of a second long with a peak power around a million Watts squeezed into a tiny fraction of a square millimetre," explains Dr Andrei Rode, the scientist who developed the unique ultrafast pulsed laser deposition system along with co-inventors Barry Luther-Davies and Eugene Gamaly at the Laser Physics Centre.

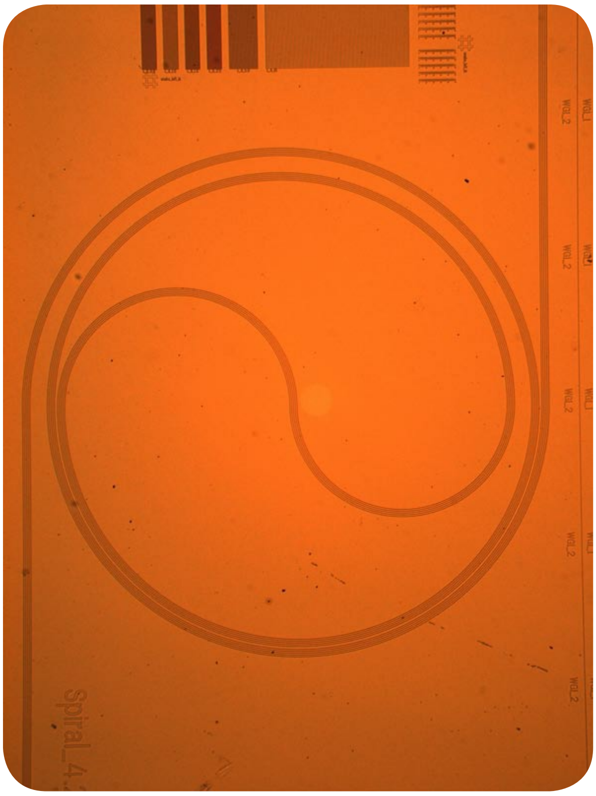
"Laser is the only clean tool where all the energy is harnessed in depositing the material you want without any contamination from the surrounding environment," says Dr Rode. "Our system is ideal for the growth of high-quality films of the desired composition without defects, which usually spoil the quality of light transmission along the films."

The second area of challenge is then taking these films and processing them into waveguides in ways that don't damage the glass. The team has crafted new techniques for chalcogenides which enable high resolution patterning and etching of the material without damaging it or introducing loss to the final device.

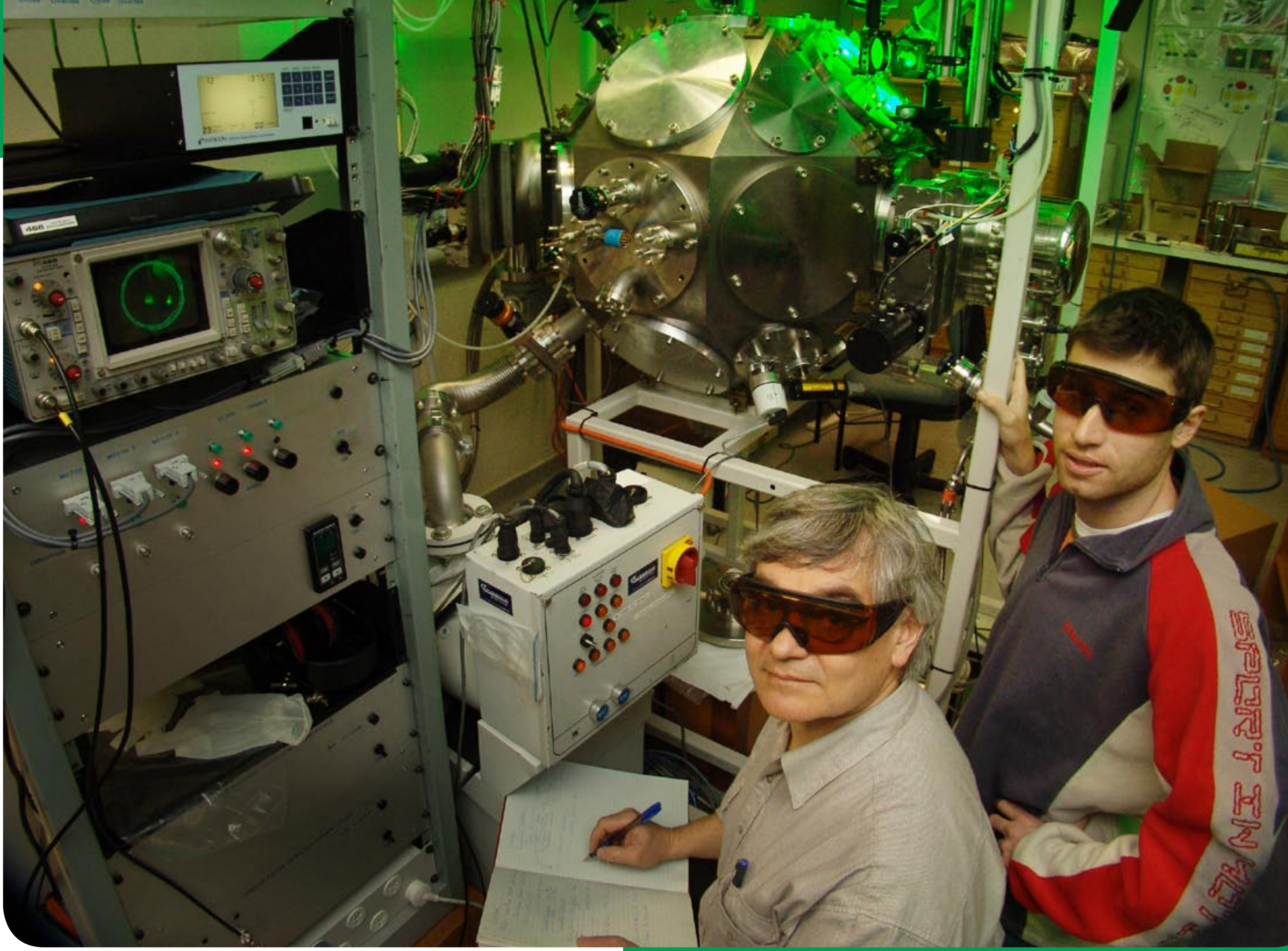
"Chalcogenide glasses are very sensitive to the chemicals traditionally used to define patterns in photoresist onto chips," Dr Madden, leader of the Planar Integration team at the Laser Physics Centre. "We've developed special etch recipes that enable us to get very smooth etch surfaces, far better than anyone else has ever demonstrated, and we've tailored the photolithography process to prevent the developer from attacking the chalcogenide. So, by combining those two steps we've been able to do very high quality handling and etching of the chalcogenide. And our methods use standard industry equipment so our techniques can be scaled up for industry.

"The advances we've made in producing higher quality films and more effective processing have produced results four to ten times better than anyone else worldwide."

The work is being undertaken within the ARC funded Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS). Their results are a huge leap towards making commercial infrared optical chips. The ANU group has successfully made optical wires up to 22 cm long that are essentially loss free.



The researchers have produced a chalcogenide waveguide measuring 22cm long, a world record

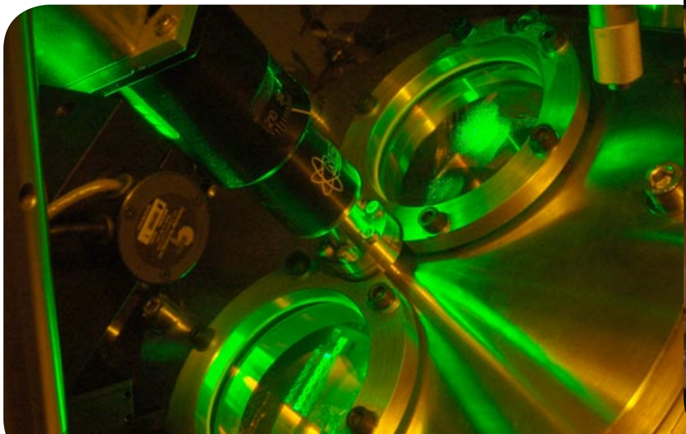


Dr Andrei Rode (left) and Nathan Madsen at work in the Laser Physics Centre

"The work we've been doing with CUDOS has been to trying to make long waveguides measured in the tens of centimetres," says Dr Madden. "Up until now the longest chalcogenide waveguides have been 6 cm long. We've now made them up to 22 cm and we're aiming for 50 cm. With wavelengths this long it's possible for non-linear processes to take place with the power of light coming out of an optic fibre. This makes these things perfect for optical chips."

In conjunction with other colleagues within the CUDOS Centre, the researchers are investigating the potential of the devices for 'All Optical' processing of ultra-high speed data traffic for telecommunications networks. As there are no electronics involved in this type of processing, it is expected that such devices may be able to process data at rates a hundred times faster than electronic systems. In collaboration with the Danish Technical University all optical multiplexing at 640 Gb/s has already been demonstrated using an ANU device, illustrating the promise of this revolutionary technology.

Below: Dr Douglas Bulla tests a photonic chip



Antimatter Matters

Exploring the Potential of the Australian Positron Beam Line Facility

Most of the fundamental particles of physics have an associated antiparticle with the same mass but opposite electric charge. In the case of electrons, their antiparticle is the positron, which carries a positive charge. A group of scientists at the ARC Centre for Antimatter-Matter Studies (a collaboration of Australian universities and research institutions) have recently completed a dual beamline facility at ANU for the study of positrons. The scientist leading the development of the Australian Positron Beamline Facility is Dr James Sullivan.

"This facility will provide us with a new tool to study the basic processes underlying positron physics. How they scatter off, and interact with, atoms and molecules of matter and how they ultimately annihilate by combining with their antiparticle." Dr Sullivan explains. "Essentially, we are interested in understanding the detail of the quantum mechanical processes that underpin such interactions."

There is a great potential to expand our knowledge of science using positrons but they also have a number of very practical applications. One is Positron Emission Tomography or PET - a medical imaging technique in which a small quantity of positron emitting radioactive isotope is bound to a biological molecule, such as glucose, and injected into the patient. When the emitted positrons annihilate a pair of gamma rays are emitted. By monitoring the position and direction of the gamma rays, it's possible to determine the location of the isotope/molecule complex within the body. PET scans are particularly useful in detecting local changes in biochemistry which often occur before the structural tissue changes that appear on other scans.

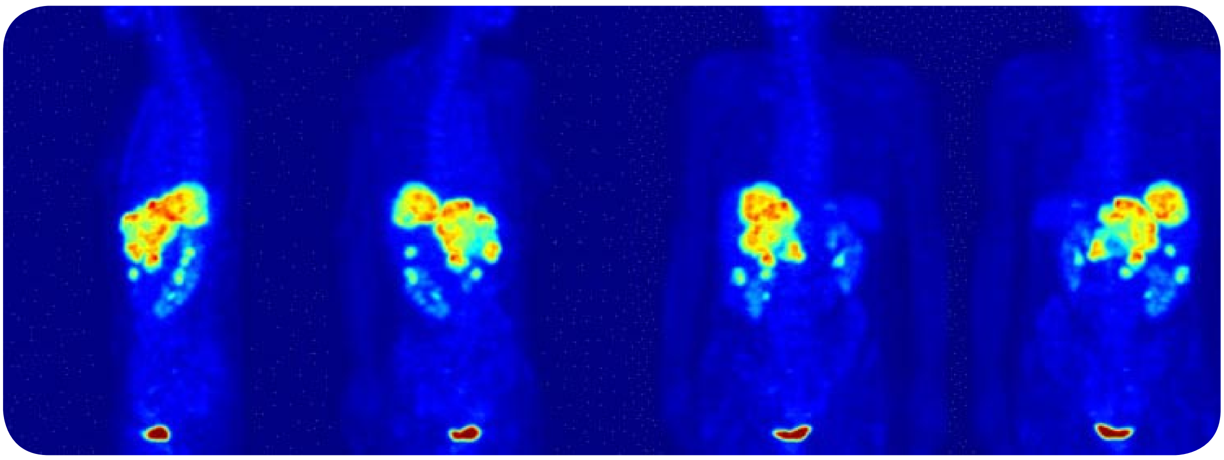
"Despite the usefulness of PET scans, the basic physics of the positron electron annihilation process is not well understood," Dr Sullivan says, "perhaps if we can get a better handle on the physics, there may be opportunities to improve the resolution of scans and or reduce the necessary dose of radioactive marker."

Science often works like this. A thorough understanding of what's going on at the fundamental level often enables technological breakthroughs that can't be achieved by simply refining the engineering.

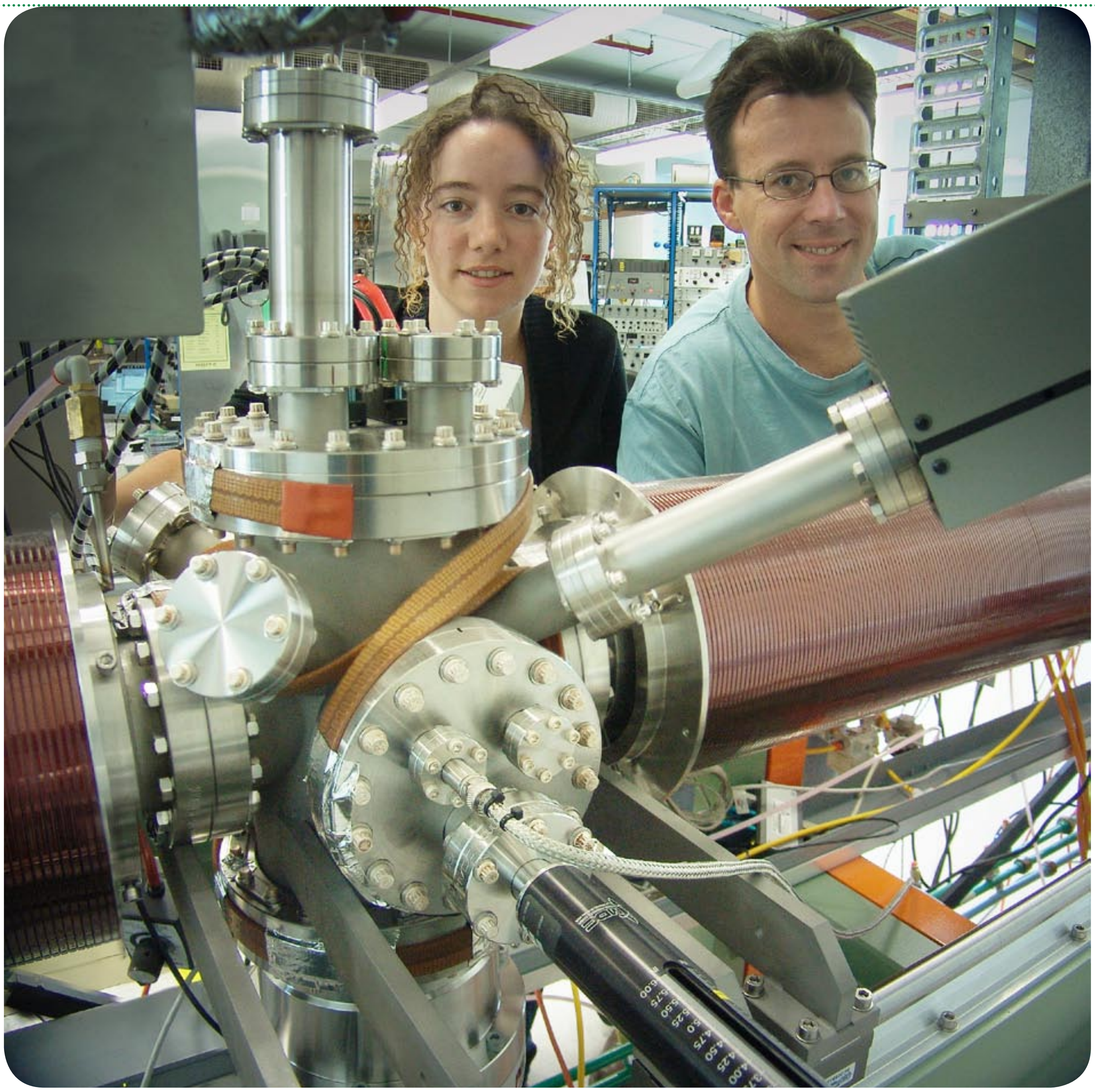
The second beamline of the facility is devoted to materials science. When positrons enter matter they commonly join with an electron to form a short-lived exotic atom called positronium. In vacuum, orthopositronium has a lifetime of 140ns but in solids this can be reduced to a few hundred picoseconds. However, orthopositronium is attracted to voids in solid material and because these act like tiny vacuums its lifetime is extended where voids are present. In effect this means that by injecting a very short pulse of positrons into a material and measuring the timing of the gamma ray annihilation signatures, scientists can determine the size and density of imperfections in the material. This is especially useful for example, in high grade silicon used in microelectronics and in detecting early signs of fatigue in metals.

But given that antimatter and matter annihilate on contact, how do you create a positron beamline in the first place?

The positrons in the Australian Positron Beamline Facility are generated as a radioactive decay product of an isotope of sodium ^{22}Na. The positrons emitted by the sodium source emerge at every angle and with a range of energies up to about 500keV. This energy spread creates a problem because the resolution of most measurements that can be made with positrons depends on the energy variation within the initial



Positron Emission Tomography image of the human body. Image: Jens Langner, Forschungszentrum Dresden-Rossendorf



Dr James Sullivan and PhD student Violaine Vizcaino with the Australian Positron Beamline Facility

beam. Scientists get around this using what's known as a moderator.

A common choice of moderator is tungsten. When the positrons enter the tungsten they very rapidly thermalise, that is dissipate any excess energy and slow down to the same speed as the electrons in the material. However, the work function of materials like Tungsten is negative for positrons so they tend to be very quickly ejected again. Of course quite a large number recombine and annihilate within the moderator, but those that don't, emerge with a much narrower range of energies than when the beam entered.

In the Australian Positron Beamline Facility, the chosen moderator is frozen neon gas rather than tungsten because the rate of annihilation is far lower in neon than in tungsten. To capture as many of the positrons as possible the neon is frozen directly to the radioactive source casing. The moderated low energy positrons that emerge from the neon are channelled into a positron trap using electric and magnetic fields. The trap further reduces the energy of the positrons and concentrates them in space. The scientists then use these trapped positrons as a reservoir from which to make a positron beam.

For experiments on the first beamline where low energy spread is required the positrons are accelerated from the trap using electric fields and directed through a gas of the target atom or molecule. In the second beamline devoted to lifetime experiments, the positrons are compressed into a series of very short (<1 ns) and compact pulses and implanted into the material to be studied.

Monsters of the Deep

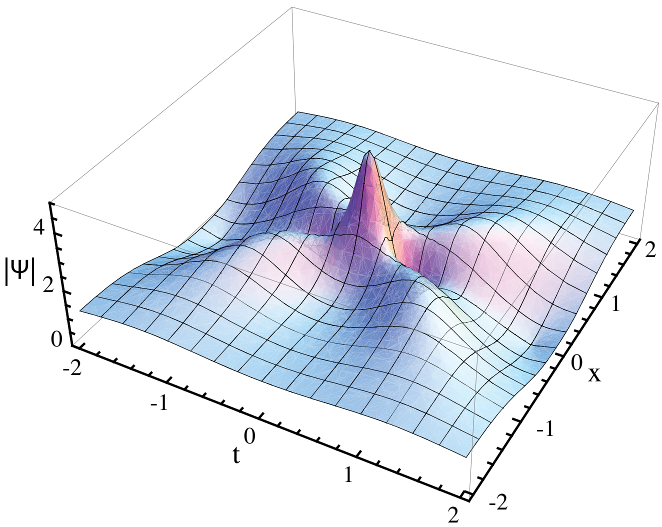
How Nonlinear Optics is Shedding Light on Rogue Waves

The history of seafaring is filled with romantic stories of far-away lands and fantastic things. Some of these can be dismissed as fanciful sea stories, but others may turn out to have a grounding in real physics. One recurrent report is of rogue waves - giant walls of water that seem to rise out of the ocean from nowhere and disappear just as quickly. Within the laws of linear wave physics this makes no sense. Whilst two waves can meet to create a larger one, the likelihood of such an event concentrating the energy into one monster wave is essentially zero. Yet over the years, reports from experienced mariners and physical evidence of damage to ships continues to mount.

Professor Nail Akhmediev of the ANU Optical Sciences Group is a world leader in the field of non-linear optics, spending most of his time modelling phenomena like solitons and laser pulses in waveguides. But although such work is driven by a desire to improve optical devices, it may also have important implications in explaining these rogue waves.

"Waves on the ocean and light beams may seem like totally different, things, but the underlying mathematics is almost exactly the same." Professor Akhmediev explains. "There's no reason why models based on mathematical concepts like the nonlinear Schrodinger equation can't work as well for water as they do for light and quantum wavefunctions."

This is a view shared by oceanographers like Dr Kristian Dysthe of University of Bergen, who began adapting some of Professor Akhmediev's solutions of the nonlinear Schrodinger equation to ocean waves and looking at the higher than usual waves they predicted.



Second-order rational solution of the nonlinear Schrodinger equation simulating the behaviour of rogue waves observed by mariners

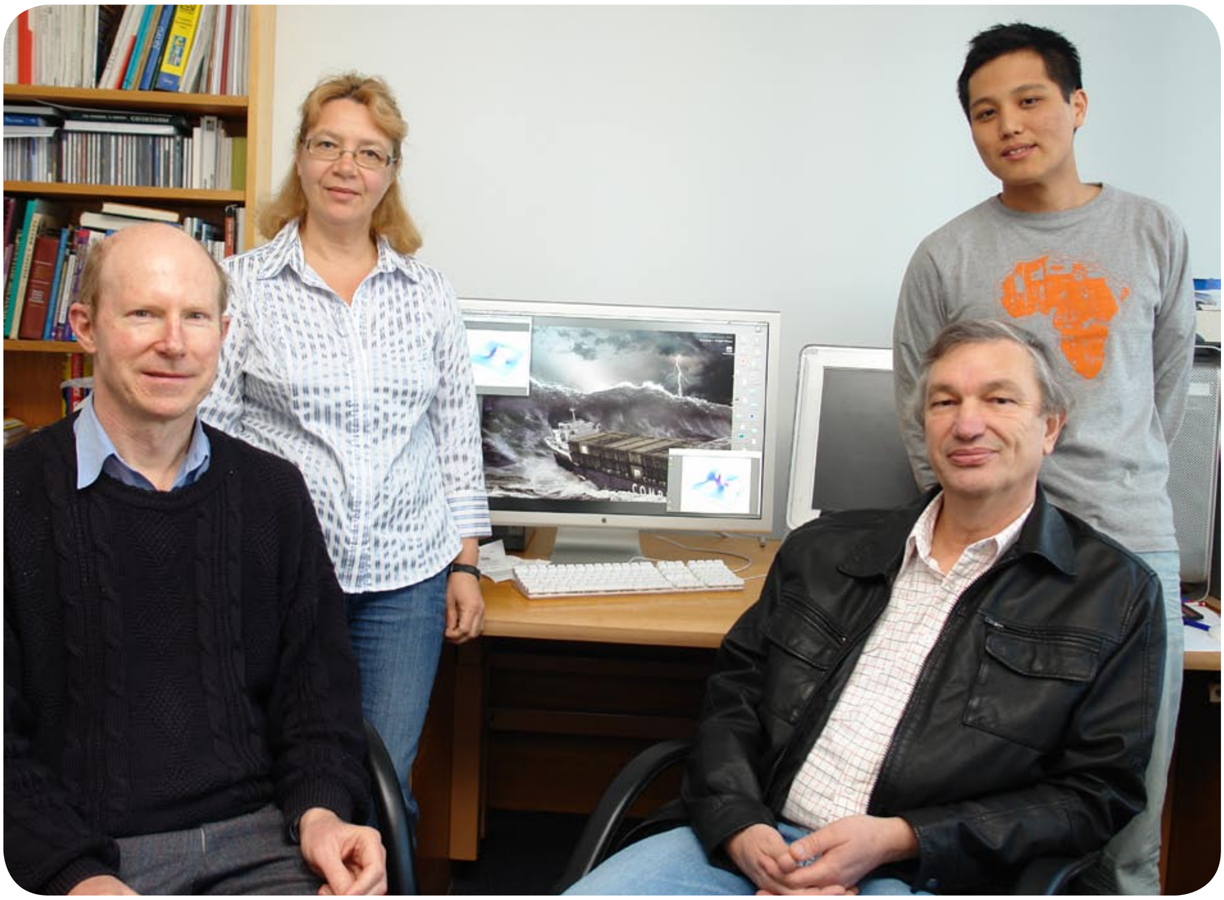
"Dr Dysthe's work really got me interested in the applications of the nonlinear Schrodinger equation to oceanography so I began to explore more advanced solutions that might account for rogue waves exactly as they've been described by mariners."

One particular class of solution presents a scenario where two waves amplified by nonlinear effects occur in the same place at the same time purely by coincidence. This leads to further nonlinear behaviour resulting first in a great hole appearing in the water followed by a massive peaked wave many times higher than the average wave height in the local conditions.

This is an almost perfect description of an incident experienced by the passenger liner Queen Elizabeth II back in 1995. The captain is quoted as saying "The ship's bow dropped into a "hole" of a trough behind the first wave and was hit by a second wave of between 91 and 96 feet high that cleaned a mast right off the foredeck." Fortunately none of the passengers or crew were injured and the ship survived, but not every vessel hit by a rogue wave has been so lucky. In 1978 the 37,000 ton MS München, a modern and well maintained ship, was lost with all hands. Although no one can be certain of the cause, the ship's lifeboat was found with damage to it's mountings suggesting that it was torn from the davits almost 20m above sea level by some huge force.

An accumulation of such incidents lead the European Union to set up a program called MaxWave to gather data on wave behaviour. 30,000 satellite snapshots of the ocean surface each 5 by 10km wide were analysed to investigate the frequency of rogue waves. Based on the MaxWave dataset, scientists have been able to calculate that at any given time there are something like ten rogue waves somewhere on the planet. Fortunately the oceans are very big and these waves are relatively localized so the chance of one hitting a ship is quite small. However given the hundreds of thousands of ships at sea every day, that small chance is definitely not zero.

It's estimated that one ship every week disappears in unexplained circumstances and whilst many are small and poorly maintained craft that may have sunk due to lack of seaworthiness or human error, many others are not. 200 large modern ships have been severely damaged or even sunk by huge waves in the last 20 years. Such waves can reach incredible heights and when they crash into the side of a ship the force exceeds 100tons per square meter. Way higher than and steel structure is designed to come with.



Dr Adrian Ankiewicz, Natasha Devine, Wonkeun Chang and Professor Nail Akhmediev of the ANU Optical Sciences Group

Unfortunately, understanding the mechanisms behind rogue waves doesn't mean that they can be easily predicted. There are some regions of the world where they occur with increased frequency such as the southern tip of Africa, where the Agulhas current flows along the coast. But they also occur in the deep ocean where there are no such currents. "There are so many variables that the behaviour of ocean waves is a highly chaotic system," Prof Akhmediev says, "So although there are conditions like bad weather and current flows that increase their probability, when and where they appear is largely just a matter of chance."

"But this doesn't mean it's hopeless. You never know what will happen in the future. Maybe now we understand what's going on one day it will be possible to predict or even disrupt such waves as they begin to form near ships."

Professor Akhmediev and Dr Ankiewicz have recently found important new solutions for wave patterns, and these could be used to explain the formation of the rogue waves, or even find areas where they would not occur, thus benefitting shipping.

Coming full circle, these strange non-linear energy concentrating ocean waves may now lead to advances in optics, possibly explaining mysterious energy spike damage sometimes seen in fibre optic infrastructure.

"We have begun to study rogue waves in optics. If they can be so powerful, we began asking ourselves, why not see if we can deliberately generate them and harness that energy in a useful way?"

A huge wave looms astern of a ship in heavy seas. Image: NOAA Photo Library

QED. We Think?

Putting Quantum Electrodynamics to the Test

Quantum Electrodynamics (QED) is a complex theoretical description of the way collections of electrically charged particles interact with photons. For example when an electron decays from an excited level in an atom, QED can predict with amazing accuracy the energy of the photon that will be emitted.

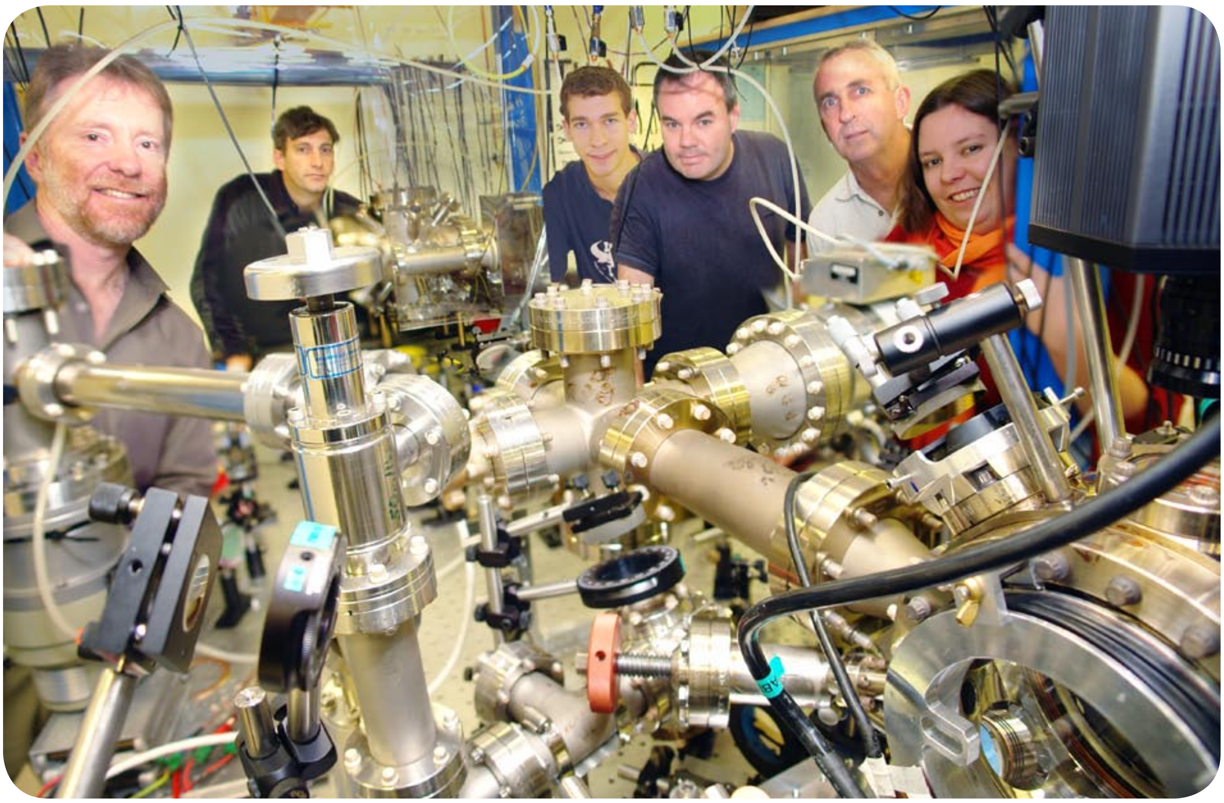
QED is remarkable in that it has been one of the most successful theories in the history of physics. Since it's development in the 1920's it has also been one of the most extensively tested with literally thousands of diverse experiments probing the various predictions of QED. And in every case QED's predictions turned out to be spot on.

For this reason it came as a huge surprise to scientists when recent experiments showed a small discrepancy between the measured fine structure of the 2^3P triplet state of helium and the predictions of QED. As other researchers confirmed that the measured energy level is slightly, but significantly different to the predictions, the scientific mystery became more and more intriguing.

Amongst the international scientists taking note of this was Professor Ken Baldwin of The Australian National University. Professor Baldwin is part of an experimental laboratory led by Dr. Andrew Truscott, comprising research fellow Dr. Robert Dall and postgraduate students Sean Hodgman and Lesa Byron. Dr. Truscott and his team are one of only four world-wide that have succeeded in cooling metastable helium into the quantum realm where Bose-Einstein condensation (BEC) occurs. Since BEC techniques employing laser cooling and magneto-optic trapping are ideal for confining and isolating a cloud of helium atoms in ultra-high vacuum for extended periods, the team decided to use the facility to investigate the anomalous 2^3P state.

This particular experiment aims to make precise measurements – for the first time - of the lifetimes (as opposed to energies) of the 2^3P_1 and 2^3P_2 states as they decay to the helium ground state. In addition, the measurements set an upper bound on the decay of the 2^3P_0 state which is predicted to be completely forbidden.

The same technique also enabled the most accurate measurement yet of the lifetime of the 2^3S_1 state, which at ~8000 s is the longest lived neutral atomic state thus far discovered. This 'metastable' atomic state is important in wide range of technological devices and naturally occurring phenomena, since like the 2^3_P states it is highly energetically excited (containing some 20 electron volts of energy as well as being very long lived). Professor Steve Buckman, an electron physicist who was involved in the metastable lifetime



Members of the research team with an atom trap

measurements, comments that "metastable helium is important to the physics of the ionosphere, gas discharges and gas lasers as it enables the 'storage' of large amounts of energy for long times."

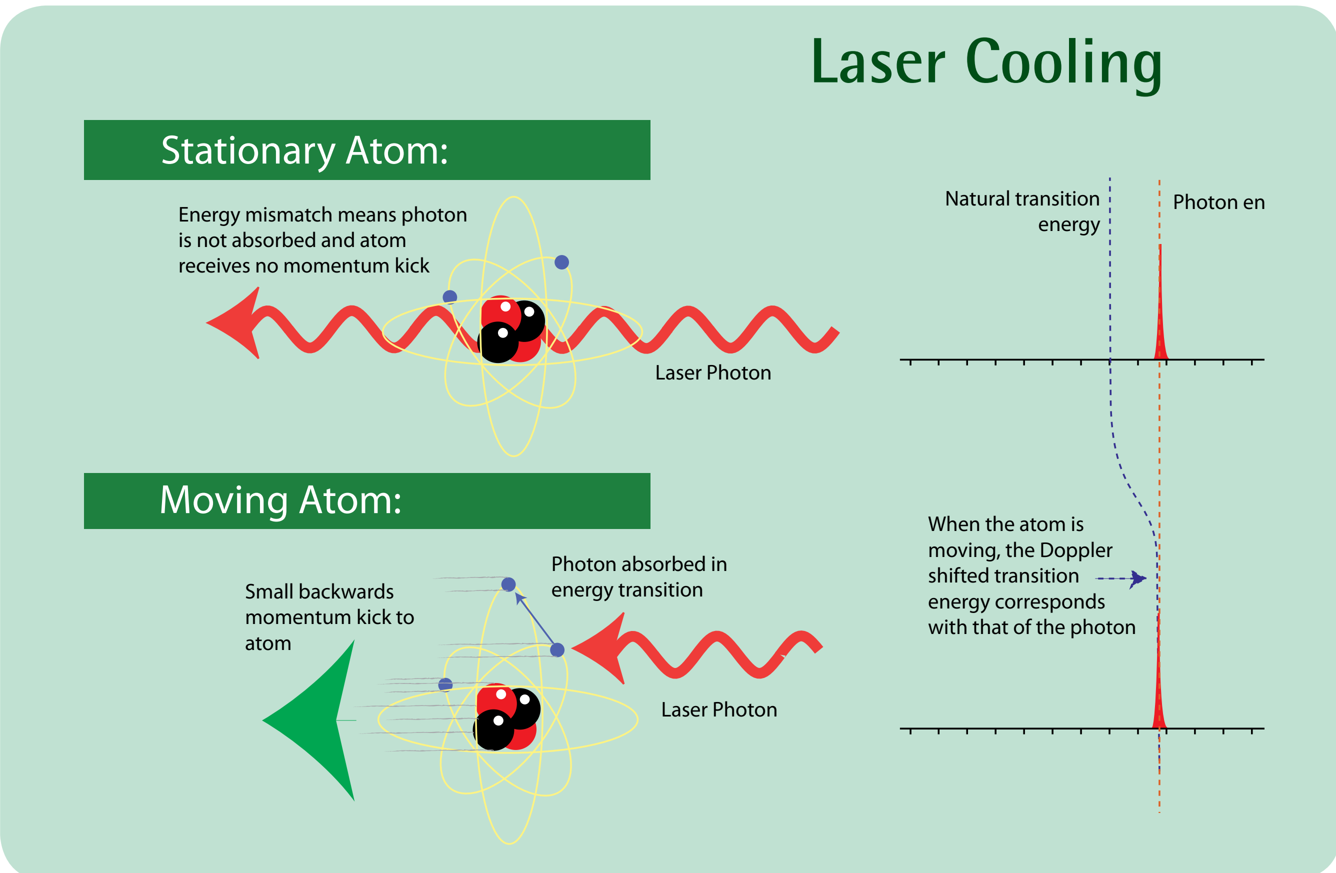
The tremendous advantage of the ANU facility is that it can routinely trap an atomic cloud for several minutes – a comparative eternity on the atomic scale. The decay of these states to the ground state results in the emission of a characteristic extreme ultraviolet (XUV) photon. So if you can hold your helium atoms for a long enough time in a small space under ultra high vacuum, you can count the emitted XUV photons and deduce the decay time. The longer you can hold the atoms in an undisturbed environment, the more accurate the measurements will be.

The lifetime results measured at ANU were in precise agreement with the predictions of QED. "These lifetime measurements are a reassuring validation of QED theory," Professor Baldwin says, "But the discrepancies in the helium 2^3P energies measured elsewhere by other groups remains. And because those measurements have been done by different people using different methods it would appear that the anomaly is real."

"Both experimentalists and theorists need to work hard to resolve this."

Theoretical calculations of the energy levels of multi-electron atoms are hugely complex and often expressed in terms of the summation of an infinite sequence. It's possible that assumptions about the convergence of these series or the cancellation of higher-order terms are not correct. Alternatively it's possible that this small anomaly is our first glimpse at something new and exciting. Observations of tiny discrepancies in the orbit of Mercury in the nineteenth century that couldn't be explained by Newtonian mechanics turned out to be our first glimpse of relativity, although no one knew it at the time.

No one is quite sure of what's going on yet, but Professor Baldwin believes there's a possibility that it might be something exciting. "The energy level measurements enable physicists to measure the atomic fine structure constant (alpha) with unbelievable precision. One thing physicists are interested in doing is making these measurements several years apart to determine if alpha has changed. One of the great questions in physics is, "Are the fundamental constants of the universe really constant?" And this may well be a good test of that."



Atoms can be given a small momentum kick when they absorb a laser photon in an electron energy transition. If the laser is tuned slightly away from the transition energy the laser photons will not be strongly absorbed. If however, the atoms are moving towards the laser, the transition energy will be slightly Doppler shifted towards the photon energy. This increases absorption and thus momentum transfer to the atom in effect slowing it down or cooling it. Once the atom has slowed, the Doppler effect is removed and absorption ceases.

Stringing a Theory Together

Can String Theory Provide the Elusive Theory of Everything

When we think about symmetry, most of us picture an object that looks the same when reflected about itself. The human face is a good example; draw a line down the middle of the nose and the left half is essentially a mirror image of the right. But this is just symmetry in three dimensions. The symmetries that excite physicists and mathematicians probing fundamental questions about the structure of the universe are far more complex. They often involve multiple dimensions, or are conceptual symmetries in which members of a system of elementary particles each has an equivalent partner particle.

In what is known as the standard model of particle physics, particles such as electrons are described by an infinitely small point in space. This point can then move through 3 dimensional space, or even an extended multi dimensional universe, and as it does so creates what physicists call a "world line". For example, the world line of a cannon ball is a parabola extending from the muzzle of the cannon to the point of impact. In a similar but much more complex way, all the bosons and fermions that make up the universe can be described in terms of infinitely small points on world lines.

So where does symmetry come in? Some physicists believe that the universe is organised along super-symmetrical principles, each particle has a symmetrical twin of identical mass and charge - creating so called super-symmetry.

Adding supersymmetry to the standard model, makes the mathematics far more elegant. Infinities that arise from fermions tend to be cancelled by those arising from their supersymmetric partner bosons and visa versa.

However, with or without supersymmetry, the standard model has a problem. It doesn't describe quantum gravity and including it in a naive way gives rise to inconsistencies. This rules out the standard model's contention as a unified theory of everything.

This is where many scientists believe that the relatively new field of string theory may lead to a breakthrough. Rather than describing the universe as points, particles are described as vibrational modes of one dimensional strings in much the same way as the strings of musical instruments generate different tones. In a closed string theory the string forms a loop. If you imagine something like a rubber band in which the rubber gets progressively thinner and thinner whilst the loop remains the same size, you approach a string. Unlike the particle (or a cannon ball) the string traces out tubes in four dimensional space creating a world volume.

Real particles often collide or fragment into sub particles and the standard model describes the resulting world line using 29 additional parameters (if we include neutrino mass). Professor Peter Bouwknegt, of the ANU Mathematical Science Institute explains that "In the ten dimensional spacetime of string theory, only a single parameter is required to describe the world volume making the mathematics a lot more elegant. Although additional parameters do have to be introduced when condensing the system down to our familiar four dimensions."

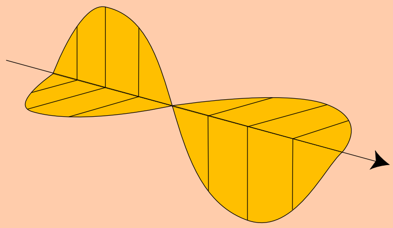
What are Fermions and Bosons?

Physicists divide the particles of the universe into two distinct groups, Fermions and Bosons. The two are distinguished by their "spin" which is a quantum mechanical parallel of the angular momentum possessed by a rotating body. Bosons have integer spin 0, 1, 2, 3 etc. Fermions half integer spin 1/2, 3/2, 5/2 etc.

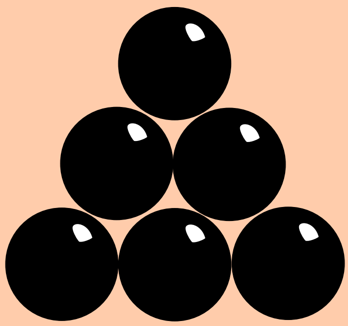
The practical upshot of spin is that it affects the way in which particles behave and consequently dictates the statistical models that describe them. Bosons obey Bose-Einstein statistics whilst fermions obey Fermi-Dirac Statistics.

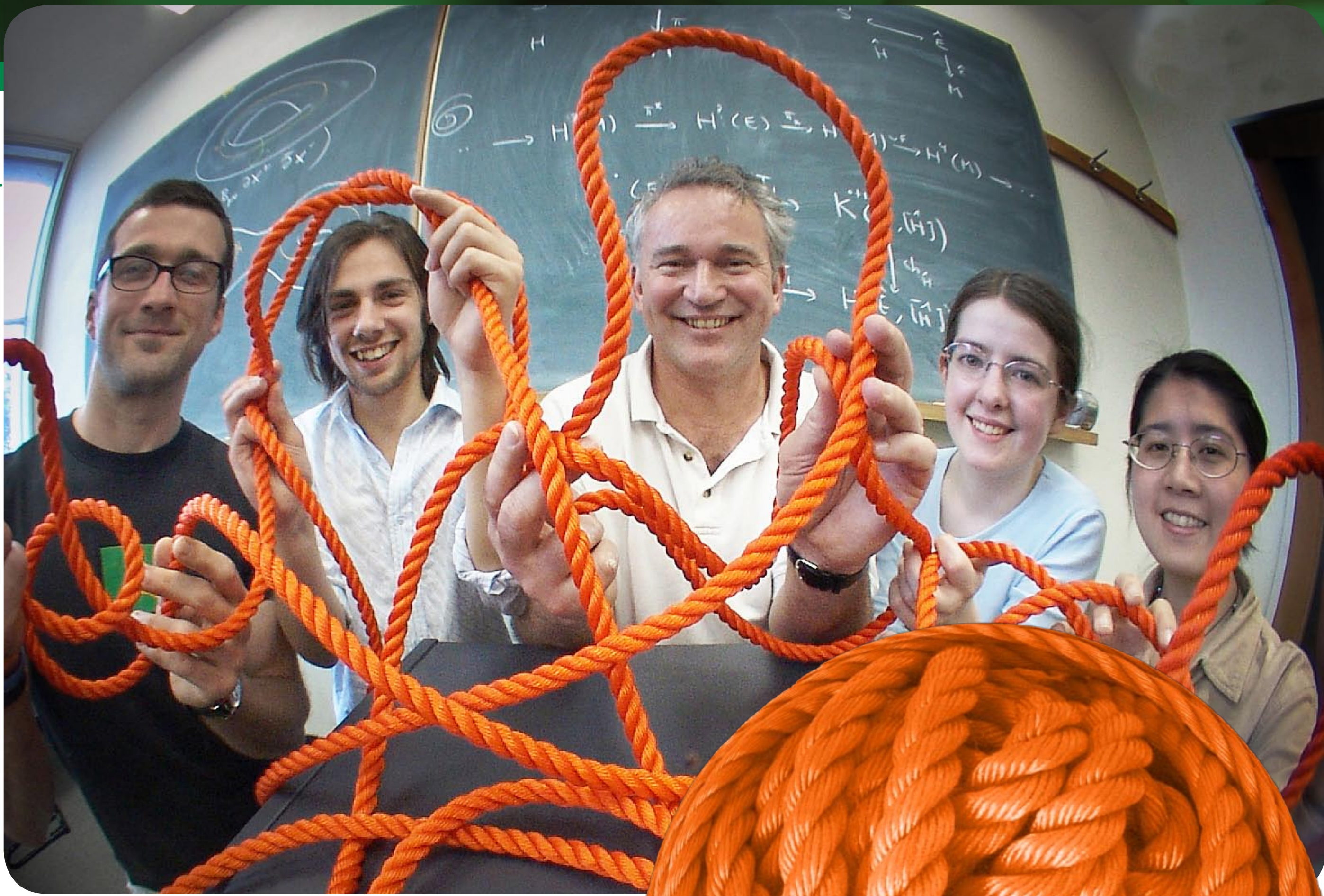
Without getting too technical:

Bosons are particles that transmit force like photons of light or heat transmitting phonons.



Fermions are particles of matter like electrons, protons and neutrons.





Some members of the ANU string theory group (L to R) Alex Flournoy, David Botman, Peter Bouwknegt, Madeleine Smith and Peggy Kao.

The mathematical elegance of string theory raises the hopes of many scientists of finding the elusive Theory of Everything. But why do physicists think that a theory of everything should exist in the first place?

The four fundamental forces that describe the universe; Gravity, the electromagnetic force the strong nuclear force and weak nuclear force may all be manifestations of a single entity. This idea arises because the coupling constants between the four forces vary with energy. If you increase the energy enough, the electromagnetic force and weak nuclear force coalesce into a single entity. Increase the energy further and the strong nuclear force also coalesces. At present, scientists don't have powerful enough colliders to reach energies at which gravity also unifies with the other forces but extrapolation of the data they have, suggests that this might ultimately happen.

If this turns out to be the case, and it happens in a way the extrapolated data suggests, it would imply that the universe exhibits super-symmetry. This is not so important for the standard model, but a super symmetrical universe is critical to string theory. The existence of supersymmetyry would not of course prove current string theory models to be correct, but it would raise that intriguing possibility.

Given this, physicists are intensely interested to find out if super-symmetry does exist. Further evidence should emerge when the massive LHC collider being built at CERN reaches completion, enabling physicists to get closer to the energies at which the gravitational force coalesces with the other three.

Meantime, theorists are grappling with the immensely complex mathematical problems underlying string theory. At ANU, scientists in the Department for Theoretical Physics and at the Mathematical Science Institute are collaborating in understanding the mathematics behind string theory. This involves applying fairly recent Mathematical disciplines, such as noncommutative geometry, to string theory, but also involves developing and studying new mathematics suggested by, and needed for, a further development of string theory. A recent example of this is the discovery of a generalization of geometry, a joint effort between string theorists and mathematicians.

Space Engines of the Future

The Potential of Plasma Propulsion

Rocket propulsion is governed by Isaac Newton's third law of motion; that for every action there has to be an equal and opposite reaction. When mass is ejected from the back of a rocket engine nozzle, the rocket recoils forward. However, every kilogram of mass ejected by a rocket at a given point in its trajectory has to be lifted to that point by the rocket itself. A kilogram of propellant used in orbit will require as much as ten kilograms of propellant to get it there in the first place.

With space launch costs reaching tens of thousands of dollars per kilogram, it's important to get the most out of the least amount of fuel possible. Conservation of momentum tells us how best to achieve this. A kilogram of fuel expelled at a thousand metres per second will change the momentum of a spacecraft by ten times more than the same amount of fuel expelled at only a hundred meters per second. So the faster you make your exhaust, the more efficiently you use your fuel.

Whilst chemical rockets are the only practical method of launching vessels into space, once in space there are some innovative alternative propulsion systems. One way to achieve high exhaust velocities in space is to ionise your propellant using electrical energy and then accelerate these ions to high velocities before ejecting them out the back of the spacecraft. Such plasma based propulsion systems use propellant far more efficiently than conventional chemical rockets and have been used on recent space missions such as NASA's DAWN and the ESA's SMART-1.

A new plasma propulsion device is the Helicon Double Layer Thruster (HDLT) being developed by Professor Rod Boswell and Dr Christine Charles at ANU. As with all plasma thrusters, the principle is to eject charged particles, or plasma, at very high speeds. The innovation in the HDLT is the way the plasma is accelerated to these speeds.

The HDLT uses a phenomenon called an electric double layer, which is the electrostatic equivalent of a sheer drop. The plasma ions passing through the double layer experience a sudden and very forceful acceleration in the same way water does as it flows over a cliff. The same double layer physics are behind the awesome light show of the aurora. In this case, the charged particles of the solar wind enter the Earth's atmosphere at the poles.

"The HDLT is a beautiful piece of physics because it is so simple and has an almost infinite lifetime. It doesn't need any moving parts, any electrodes and is based purely on naturally occurring physical phenomena," Dr Charles explains.

With conventional plasma thrusters the continuous ejection of positively charged particles creates a problem. Negative charging of the spacecraft. If left unchecked this would both create havoc with the onboard electrical systems and also strongly reduce the number of particles leaving the thrusters which results is poor performance. To overcome these problems, most electric thrusters have an electron ejecting charge neutralising system that neutralises the ions leaving the spacecraft in the exhaust. These systems are prone to failure and conventional ion thrusters usual have two or three neutralisers onboard, which adds to the mass of the spacecraft. However, one of the special features of the HDLT is that due to the unique configuration of the double layer both electrons and ions are ejected from the exhaust, which ensures that the plasma leaving is neutral and that the spacecraft doesn't charge up.

Michael West

Making a successful space propulsion system is a difficult business. Space engineers don't have the luxury of flying one prototype thruster after another in orbit until they get the design just right. Such propulsion systems have to be designed using theory and computer simulations and then tested in labs on Earth. However, it's impossible to create a vacuum test chamber that's even remotely comparable with the vastness of space. And given that the magnetic field and ion exhausts of a plasma thruster extend over large distances, you can never be entirely sure that what you measure in the lab is going to be exactly what you get in space.

Michael West is undertaking his PhD testing the HDLT prototype in conditions that simulate the vacuum of space as closely as possible in a lab. "The main thing we're aiming for is to immerse the entire thruster in vacuum, not just the exhaust port. If in addition, we can make the chamber as big as practical, we're optimistic that we're getting pretty close to actual space conditions." He explains.

One of the most important parameters of any rocket engine is how much thrust it produces. With a chemical rocket this is relatively easy to measure because such engines produce a very large thrust for a very short time. You mount the engine on a jig, fire it up and measure how much force it exerts against a fixed mount. However with a plasma propulsion system it's not so easy because they produce a very small thrust for a very long time.

"It's a bit like paddling a canoe" Michael explains, "You can paddle like crazy until you're worn out, then coast along with the momentum you've built up, and that's like a chemical rocket. Or you can paddle gently all day, gradually increasing your momentum, which is more like electric propulsion."

In the frictionless environment of space, a milliNewton of thrust applied for several months will slowly accelerate a 1000 kg space ship to huge speeds. But on Earth it's very hard to measure this tiny thrust by just monitoring the force on the back of the thruster assembly. To get around this, Michael developed a simple but effective thrust measuring instrument. A silicon wafer is attached to the end of a rod, which is suspended on a pair of knife edges. This creates a pendulum-like structure. When the plasma exhaust from the thruster hits the wafer it displaces it from vertical – the larger the thrust, the greater the displacement. In order to measure the very small displacements, Michael uses a laser bounced of the back side of the wafer and directed to a CCD sensor some distance away. Using this device, he is able to measure thrusts of a few microNewtons – about the force an ant's foot exerts on the ground.

The team are now using the thrust measurement system and simulation chamber to explore the possibility of operating the thruster in a super-bright high density mode, which generates about seven times the ion flux of normal operations. The group have collaborated with the European Space Agency during initial development and testing of the first HDLT prototype.

Michael explains, "Highly efficient electric propulsion systems like the HDLT are exactly what you need for manned flights to Mars. The idea is that a series of unmanned cargo craft use plasma propulsion to take a long, slow but super-efficient route to Mars. Because of the efficiency of the thruster the mass of cargo would be far higher than conventional rockets could carry. Once the supplies are all in place at Mars, you can send the astronauts on a conventionally powered express trip."

When asked how he first became interested in space, Michael explains. "When I was in year nine I had a really enthusiastic science teacher, a real mad professor type!" He encouraged a group of students to enter a NASA sponsored competition to design an experiment for the Space Shuttle. Michael and a group of friends entered and won the competition. The prize was an expenses paid trip to see a Space Shuttle launch and a behind the scenes tour of NASA. "From that point on I was hooked," he says, "I had to become a space scientist." Proof positive that inspirational teachers make a huge difference to the lives of their students.

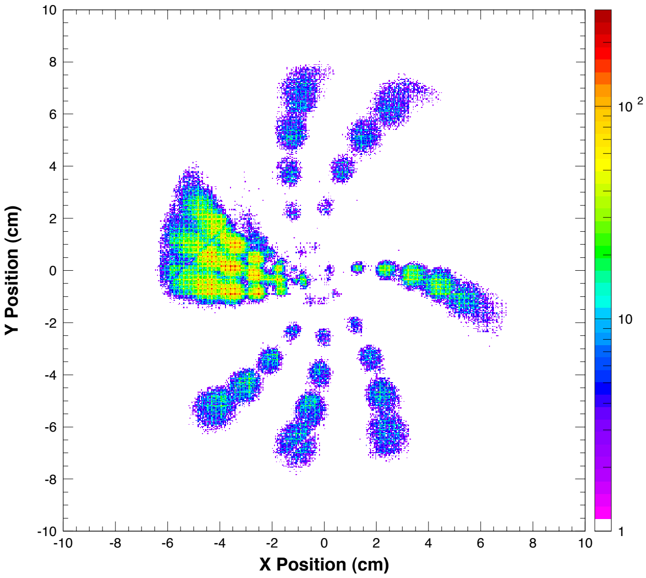
The exhaust of the HDLT in a space simulation chamber

Miniature Universes Collide

Using Nuclei to Probe the Quantum/ Classical Boundary

A century ago, physicists did not have a satisfactory explanation of the process that powers the sun. Some had speculated that it was a giant ball of burning coal - leading to the rather alarming conclusion that it would soon burn out! Others argued that the heat was the result of the gravitational contraction of a giant ball of gas. Although this led to a longer calculated lifetime, it was still nowhere near long enough to satisfy geologists and biologists, who called for hundreds of millions of years to explain geological structures and the evolution of life on Earth. It wasn't until the 1930's that the mystery was finally solved, when physicists discovered the true source of the sun's energy – the fusion of hydrogen nuclei to form helium.

Despite great progress since then, the mechanism of fusion of heavier nuclei is still not properly understood, and nuclear scientists today are working hard to unlock the mysteries of this fundamental process. Scientists at ANU have recently suggested that problematic experimental observations may be a result of the process of fusion being at the boundary between classical physics, where Newton's laws of motion hold sway, and the stranger world of quantum physics.



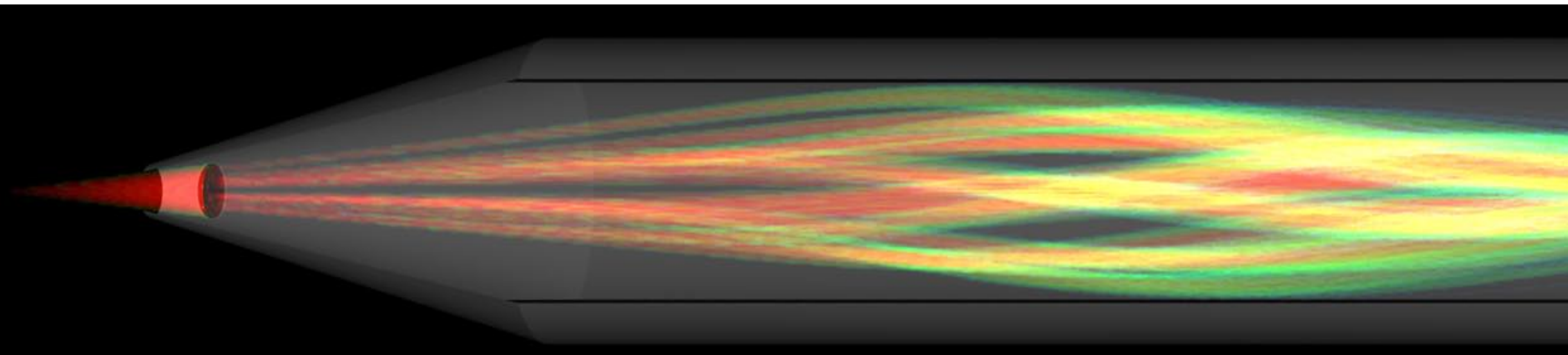
Testing the superconducting solenoidal fusion product separator: Computer simulations of trajectories through the separator are shown below, with the actual pattern measured by the position sensitive detector at the exit of the solenoid shown above

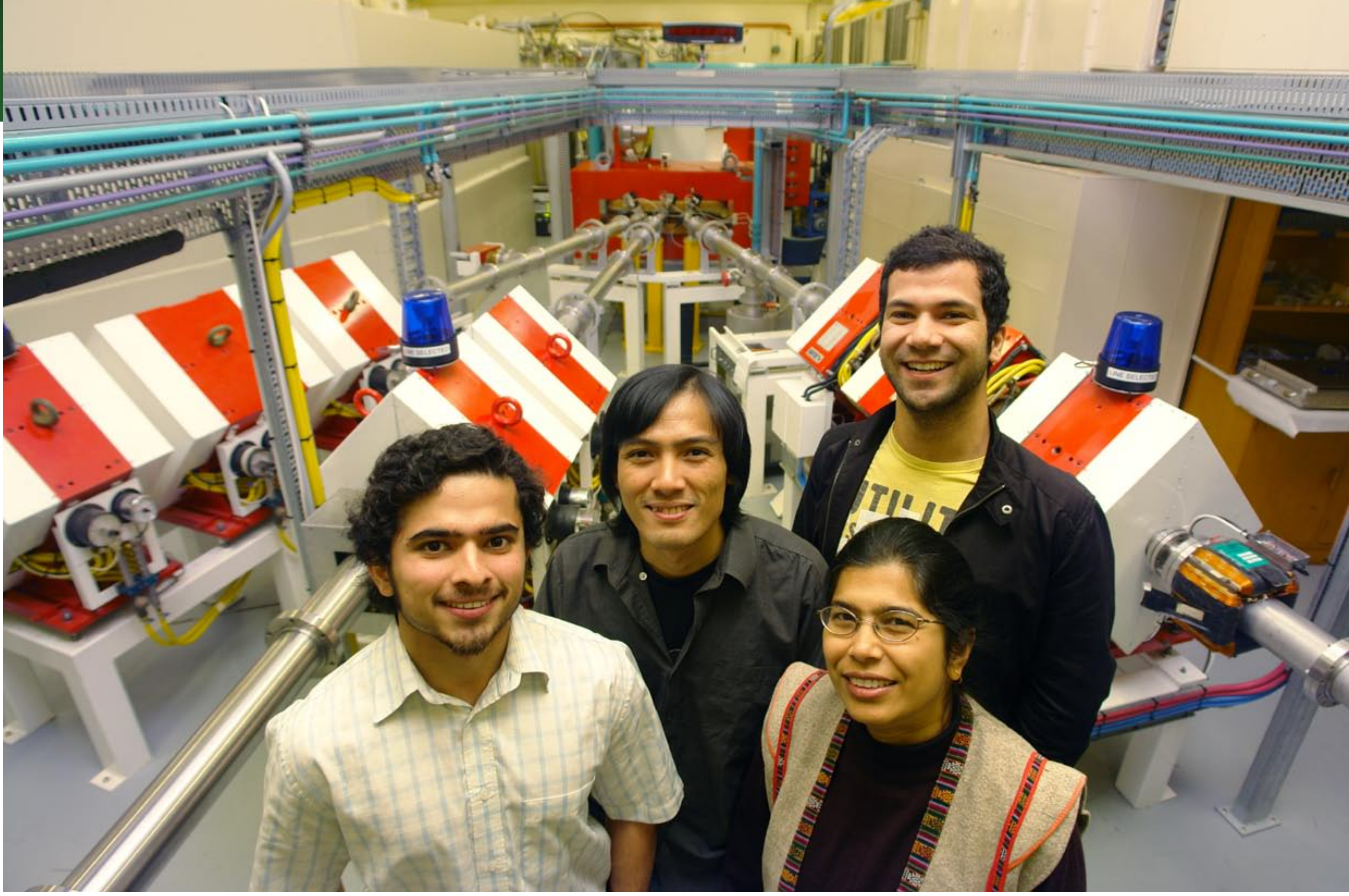
First, let's look at the fusion of two hydrogen nuclei in a classical way. Coulomb's law of electrostatics tells us that the two positively charged nuclei will repel each other more strongly as they approach closer. If they are moving towards each other slowly, this repulsion will cause them to bounce apart long before they touch. If their velocity is high enough, they will have enough energy to overcome the Coulomb barrier (think of rolling a ball over a hill) and begin to overlap. At this point, the hugely strong but very short range attractive nuclear force takes over, forcing the two to fuse, forming a single nucleus (imagine two drops of water touching and merging into one).

This classical picture sounds quite straight forward, but in the Sun, when you plug the numbers in, it doesn't lead to fusion! The thermal velocities at the centre of the sun are not sufficient for hydrogen nuclei to overcome their Coulomb barrier and fuse. And yet, as we see every day, the sun does shine! So how is this possible?

The answer lies in quantum mechanics. Quantum theory tells us that the motion of tiny particles like nuclei can be thought of as having a wave-like property. The wave-function is a mathematical expression that tells us the probability of finding the particle at any given point in space.

One of the interesting things to come out of the mathematics of wavefunctions is that they don't have sharp discontinuities. In other words they do not abruptly drop to zero at a barrier. This means that the wavefunction of a particle outside a potential barrier actually extends under the barrier, where classically, its energy is negative! The wavefunction falls off exponentially under the barrier, so depending on its thickness, there is a small but real probability of finding the particle inside the barrier. This means that every now and again, a particle can pass through a classically impossible barrier, a process known as quantum tunnelling.





Dr Mahananda Dasgupta and PhD students between the accelerator beamlines used for fusion experiments

Quantum tunnelling is what happens within the sun. A minute proportion of the collisions of hydrogen nuclei lead to fusion, creating helium nuclei and releasing vast amounts of energy in the process.

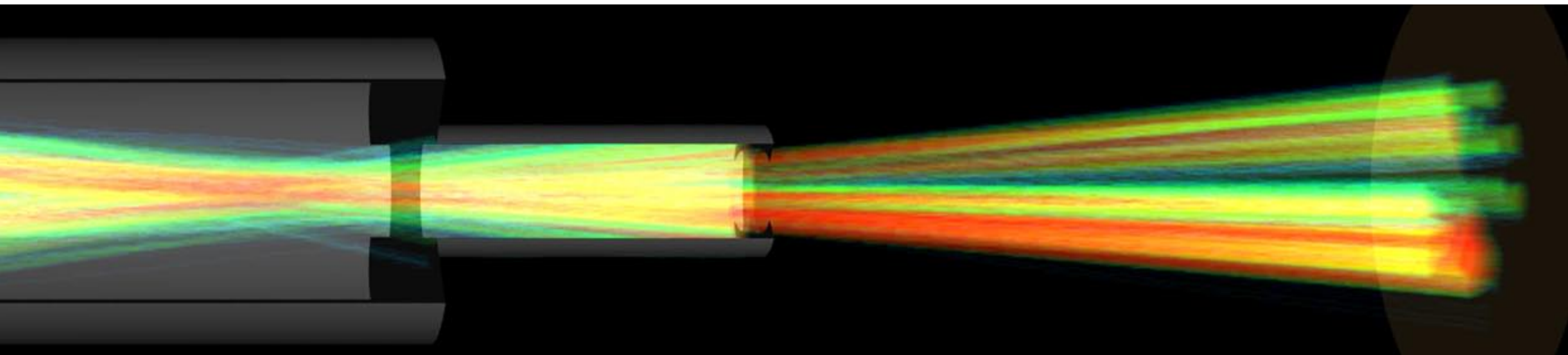
One of the key ideas in quantum mechanics is superposition, meaning that until a measurement is made a quantum system can exist in all possible states at the same time. The process of measurement forces the system to make a transition from the many simultaneous possibilities to a single outcome. One of the challenges of modern physics is to understand the transition from superposition of states (quantum world) to a single definite outcome (classical world).

Drs Mahananda Dasgupta and David Hinde are two nuclear physicists at the ANU exploring the fusion process, and the light it may shed on the shadowy interface between the classical and quantum worlds.

The nucleus is a unique place in nature because the nuclear force that binds it together is so much stronger than any of the other 3 fundamental forces of nature (weak nuclear, electromagnetic and gravitational forces) that it overwhelms them. This means the neutrons and protons inside a nucleus are effectively isolated from all external influence.

"The nucleus is a fascinating object because it's so thoroughly isolated. Each nucleus is a miniature universe in itself." Dr Hinde explains. "Prior to the moment of fusion the protons and neutrons are completely unaware of anything outside their own nucleus, then suddenly a whole new universe crashes in and all the particles re-organise themselves in a frantic burst of quantum activity." The nuclei are in a quantum superposition prior to fusion, but the reorganization of all the constituents of the two nuclei is the "measurement" that leads to a definite outcome - fusion. The question is, where does this measurement process start?

To study this Drs Dasgupta and Hinde use Australia's largest and most powerful heavy-ion accelerator at the ANU, with accelerating voltage of over



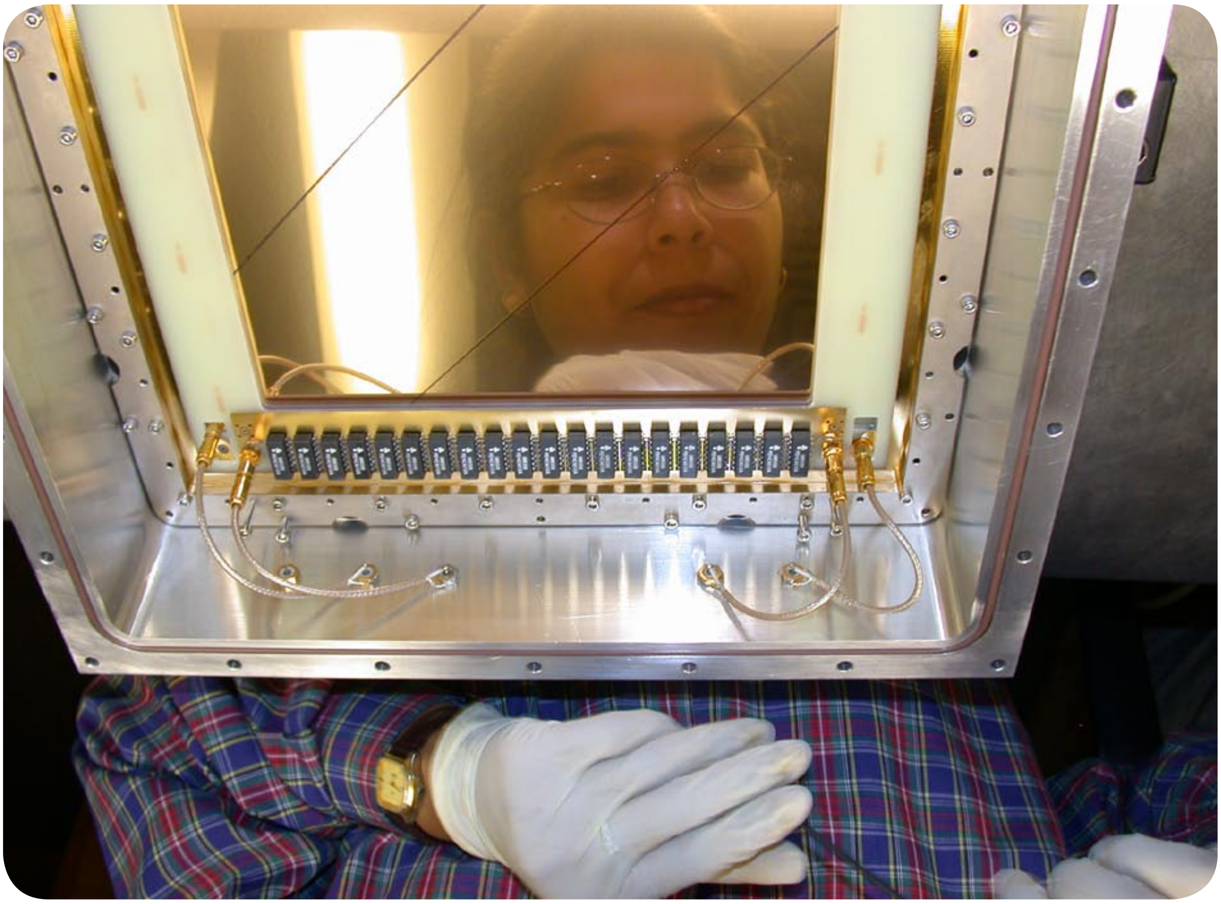
15 Million Volts. A precisely defined beam of highly energetic nuclei are directed onto a thin target foil, where they can fuse with nuclei in the target to create heavier elements. After fusion, these new heavier nuclei evaporate some neutrons, and maybe protons, emit a number of characteristic gamma rays, and finally often decay by emitting an alpha-particle (also through quantum tunnelling!). "You can't see the fusion directly but you can detect the products emitted following fusion." Dr Dasgupta says.

However even the tell-tale fusion products are not easy to observe. The space between nuclei is vast even in seemingly solid materials, so the probability of a head on collision between two nuclei is miniscule. For every direct hit there are millions of glancing collisions that simply scatter nuclei out of the beam, resulting in an intense cone of scattered nuclei mixed with a few fusion products, all going forwards. To separate the two, the team have developed a powerful superconducting solenoidal separator that generates a strong magnetic field. Because the charged particles are deflected by the magnetic field according to their mass and velocity, it's possible to focus the fusion products on their detector, and divert the scattered beam particles onto a stopper.

One of the most interesting results to come from this work so far is that the observed quantum tunnelling can be 10 times smaller that predicted by theory. Dr Dasgupta believes that this may be due to quantum decoherence.

"As two nuclei approach each other they each exist as many possible quantum states superimposed together. However when they meet and begin to combine these possibilities have to condense into a single measured reality." She explains. "So what we think we're seeing is a transition from quantum to classical behaviour during the tunnelling process. And of course tunnelling is only possible in the quantum world so the transition to classical behaviour may be strongly reducing the tunnelling effect."

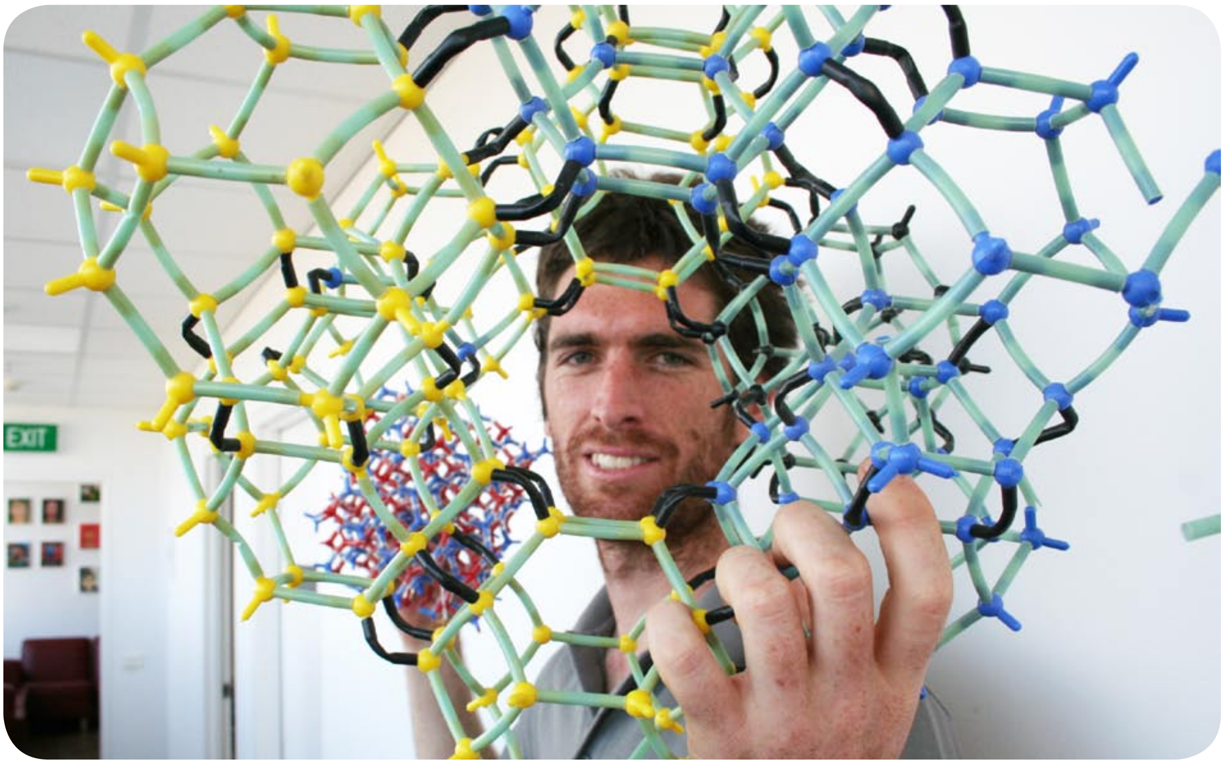
The nucleus makes a particularly interesting laboratory for quantum physics because it's such a pure and isolated system. An improved knowledge of how tunnelling nuclei behave may well lead us to a better understanding of what the mathematics of quantum mechanics actually mean in the real world.



Dr Mahananda Dasgupta assembling the position sensitive particle detectors used in fusion measurements

Knots and Networks

The Mathematics of Entanglement



Toen Castle believes we have much to learn (and gain) by subtlety modifying the connections between the nodes that make up a network, be that network a crystal lattice or a molecular material. His specific interest, which forms the basis of his PhD studies in the Department of Applied Maths (RSPSE), lies in understanding how networks of points can be entangled without changing the basic order of connection.

"This field of research started with people looking at networks that are embedded in space," explains Mr Castle. "These approaches are relevant to a lot of physical systems such as crystals because crystal lattices can be thought of as networks of atoms and bonds in space.

"However, while quite a large amount of interest has been directed towards considering the connections between elements of these networks, not so much attention was given to the more subtle effects of the manner in which connections could be made.

"And when I looked at how connections might vary I began to concentrate on features that these bonds within the network can have. It's possible to conceive of a tangling of complex structures, of things being connected in ways that are knotted or linked.

"A knot is a loop in space that you can't straighten out into a normal circle in space without passing through itself. Knottedness is a fundamental property of a loop in space. Either it's just a simple loop, like a circle, or else it's got some form of structure in it that can never be removed without passing edges through each other.

"Links are related to knots. In the link there are more components and they're joined together and unable to separate, which is a similar phenomenon, but involves two or more components instead of the one."

Knots and links add a whole new dimension to the manner in which a network performs. You can have two networks with the exactly the same connectivity but which are linked or knotted in different ways making them behave in different ways.

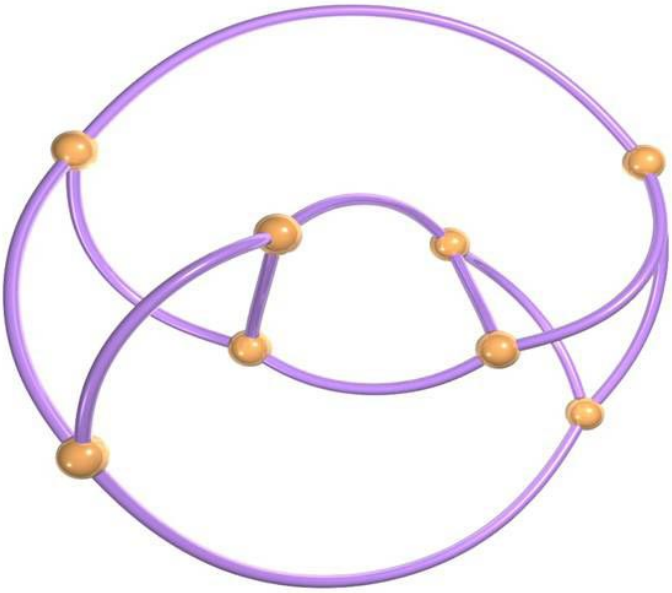
A LANGUAGE OF KNOTS

"It's very difficult to describe this area of tangled networks," observes Mr Castle. "There's no natural language to describe exactly what's going on. You can wave your hands and say 'look its tangled', 'look the layers are interlocked with each other', but in terms of a quantitative science we're really searching for a good description of what's really going on. That doesn't exist at the moment and that's what I'm trying to do with my research.

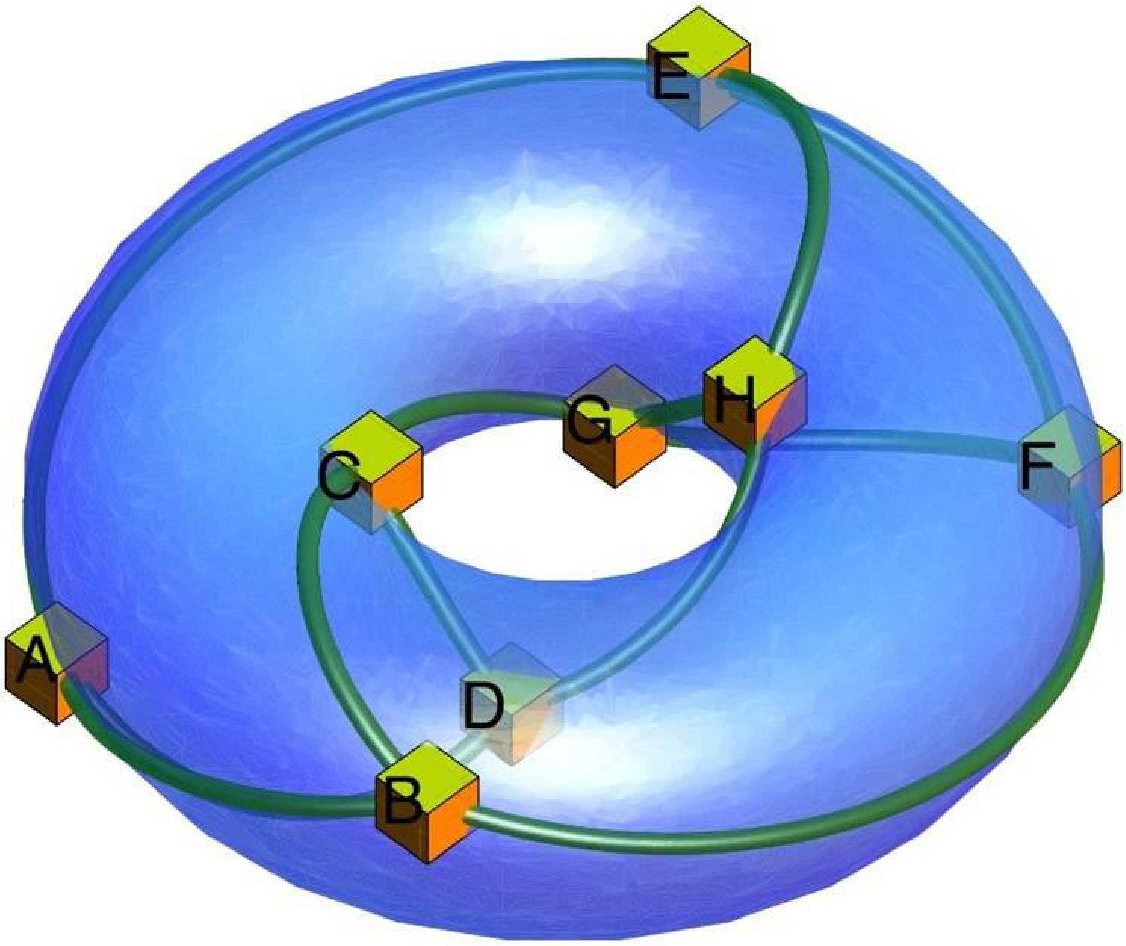
"The aim is to come up with a framework or language by which this understanding of entanglement can be taken further and applied to different networks. And to be a good language, it must describe the fundamental tangling features that can be present in a network. So, by finding a conceptual language that can describe the tangling you can put together words from this language and generate novel structures.

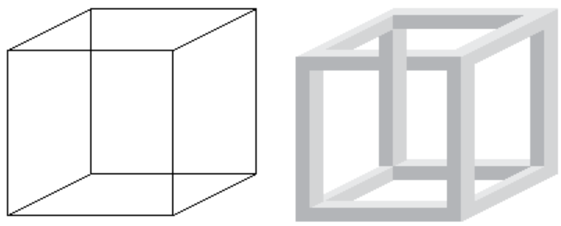
"The language we're generating is still rudimentary but we've made some real progress."

To build a language of entanglement, a language of network knots, you ideally begin with a basic structure and explore what's possible in terms of entangling it without changing its connectivity. And for Toen Castle, that structure is a cube.



This structure - shown (below) on the surface of a doughnut and (above) without the surface - have the same connectivity as the cube (8 nodes connected by 12 edges) but are structurally tangled. By understanding the language of loops and knots Toen Castle believes we can create materials with new properties.





The optical illusion of 'the impossible cube' (above), with a wire-frame version of the cube (left) and the 'impossible cube' (right). An impossible cube is really a form of a knotted cube. You can't embed an impossible cube into a sphere as you can with a normal cube. However, you can embed it into a doughnut as shown on the previous page. By figuring out ways that simple arrangements can be knotted in different arrangements you open up rich new possibilities for networks.

"Most people conceive of a cube as a solid square block with six sides," says Mr Castle. "For our purposes, ignore its volume and surface and think just of the edges as a wire frame with eight corners. The cube is a very interesting structure because it's so common and hence we have a good intuitive link with it. However, it's also complicated enough to start to display some interesting properties in terms of the potential ways to tangle it.

"It's also a common building block in crystal lattices. In complex structures, modern crystallographers may find certain repeating cubic and tetrahedral units inside the crystal structure and then represent the structure in terms of those cubes and tetrahedra or prisms just to simplify their work."

To understand how you might tangle a cube it's helpful to consider the impossible cube. It has the same connectivity as your normal cube and yet it's completely different. It's tangled.

"Many people will have seen the impossible cube in books of optical illusions," says Mr Castle. "It's an optical enigma in which the lines and perspectives seem wrong. It seems impossible because there's no way you could embed this version of the cube onto a sphere. By that I mean that there is no way to deform the wire-frame cube onto the surface of a sphere. The cube embedded on a sphere - a normal cube - can't have any knots or links.

"If you consider every way of starting at a certain vertex of the cube, travelling along edges and coming back to your original vertex without doubling up, there's no way that you can make a cycle that will be anything other than a simple loop; there's no way it can have a knot in it, being embedded on the sphere just prohibits it. In terms of tangling, the sphere isn't an exciting place to live. Similarly, there's no way to find two distinct cycles that actually link together, they're always just on opposite sides of the sphere.

"However, it's quite easy to embed an impossible cube onto the surface of a doughnut. Another way of saying that is that there's only one way you can embed a cube into a blob but there are many interesting ways you can embed that cube into a blob with a hole in it (that is, embed it into a doughnut or torus). And this is the beginning of how you build your language of entanglement."

KNOTS BEYOND THE DOUGHNUT

Having worked out a method to tangle basic structures by embedding them in doughnuts, Mr Castle is now looking to explore more complex entanglements.

"The next step in this process is to step up from the simple donut, a torus with one hole, to more complicated shapes like a donut with many holes," says Mr Castle. "This is a very big challenge because the mathematics of multiple-holed donuts is quite different to single holed donuts.

"You get a vastly more structural complexity when you use multiple-holed donuts. You can chop them up and peel them open into repeating units in any number of ways giving you very interesting twisting and tangling patterns."

While conceiving a language of entanglement might sound a little abstract, Mr Castle is a firm believer in the real world application of this work.

"While this work engages with some very sophisticated concepts, there's real potential for applying this work," he says. "Possible applications of this work include the creation of new crystal structures and new materials."

"Hydrogen storage is another big application of this work because hydrogen, being a gas, takes a lot room to store but hydrogen has an affinity to stay at the surface of some materials. So, some mineral structures like zeolites, have lots of big rings in their structure, and are excellent for hydrogen storage. Materials engineers are trying to improve this storage structure and scale it up, however when they do this, the rings are prone to collapse around each other – and entangle. So, researchers are now looking to build similar structures that have the same features, but which are more stable and avoid tangling.

"And there are other ideas as well for how we might employ tangled networks and structures. Though I suspect that the best ideas on how to use this knowledge haven't even occurred to us yet."

The Evil Twin

How Modelling the Atmosphere of Venus Helps Us Understand the Earth

One of the difficulties in modelling the climate of the Earth under various greenhouse scenarios is that scientists only have one set of parameters against which to compare such models, that is, the climate history of our own planet. When making future predictions it's hard to be 100% sure that you haven't simply tweaked your model to fit the past without the underlying science being good enough to give a degree of certainty to the future scenarios it predicts. One way this can be overcome is by looking at the atmospheres of other planets such as Mars and Venus where the parameters are different but the science is exactly the same. Venus is an especially interesting and alarming case as its dense CO_2 atmosphere has led to a runaway greenhouse effect heating the surface to temperatures that would easily melt lead.

Dr Frank Mills

Dr Frank Mills is an atmospheric and climate scientist with a joint appointment in The Fenner School of Environment and Society and The Research School of Physics and Engineering at ANU. A primary interest is numerical modelling of the chemical processes within the atmosphere of Venus. "Many of us are strongly interested in creating better models of the Earth's atmosphere and because the physics and chemistry are the same on Venus but the density and composition of the atmosphere are vastly different, it gives us an opportunity to test our models in two very different cases. If a model of planetary atmospheres holds good to observations when you plug in the pressures, densities and chemical compositions of two planets, then it gives you confidence that you've got the underlying science right." Dr Mills explains.

The Anglo Australian Telescope

Of course the problem with Venus is that it's not nearly so easy to gather atmospheric and climate data as it is on the Earth. The data that Dr Mills feeds into his models come from two sources. The first is from spacecraft such as the European Space Agency's Venus Express for which Dr Mills is a member of the scientific team.

The other way to gather Venus data is using large Earth based telescopes such as the 4m Anglo Australian Telescope in NSW. An important portion of the Earth based data for this research program has come from collaborations with Dr Jeremy Bailey of the University of New South Wales. Although it may seem strange to observe a bright planet with a 4 metre diameter telescope designed for very faint objects, the AAT has an advanced suite of spectroscopic instrumentation that make it one of the best telescopes in the world for gathering such data.

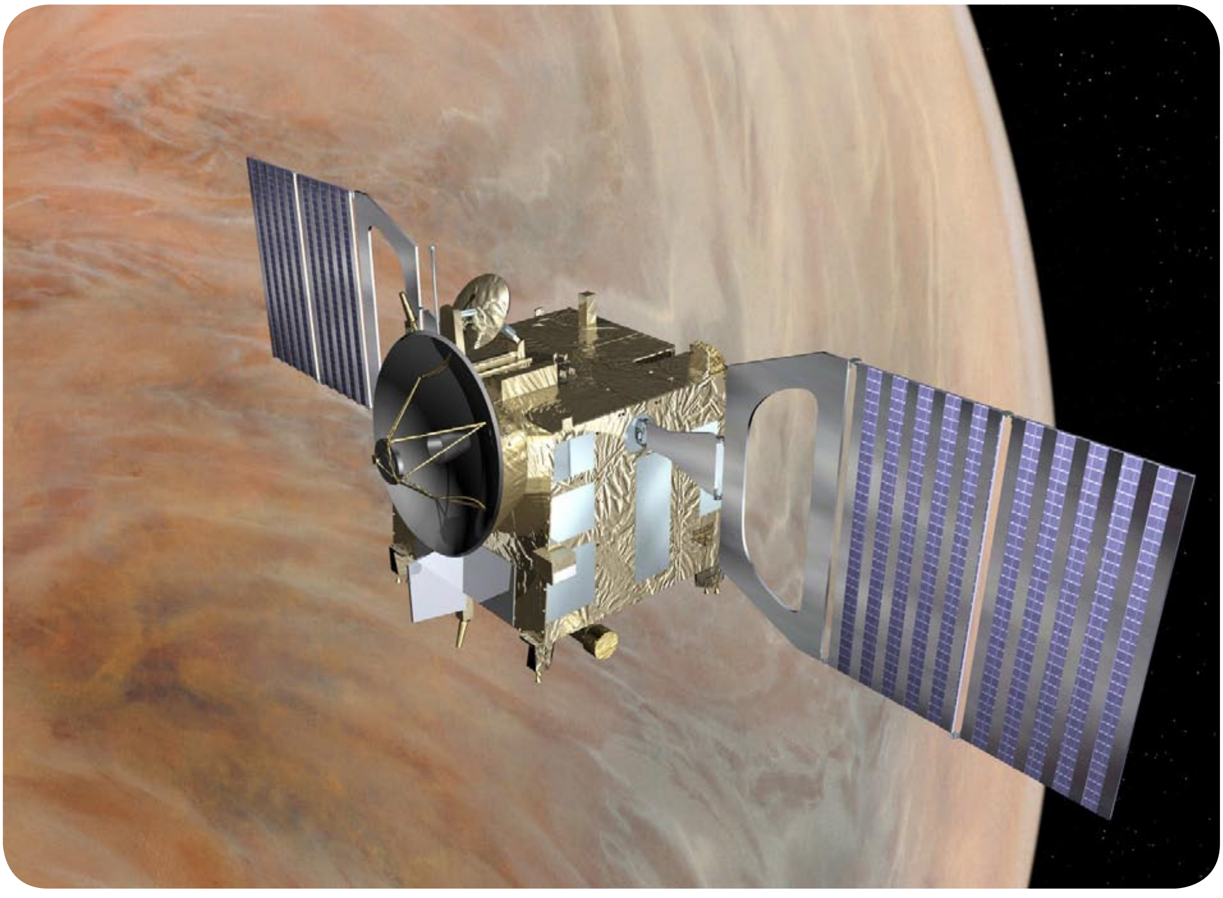
One of the difficulties with making measurements of molecular absorption lines in the atmosphere of Venus using terrestrial telescopes is that the Earth's atmosphere contains nearly all the same molecules as those on Venus so the two spectra overlap. To get around this scientists make atmospheric measurements on Venus when the relative velocity between the two planets is large enough to Doppler shift the spectral lines from Venus away from the terrestrial lines. This makes it possible to distinguish the Venus spectrum from that of the Earth's own atmosphere.

Within the atmospheres of planets, chemistry, thermodynamics and convection combine with solar radiation and surface interactions to create a highly complex and dynamic system. The high densities and temperatures on Venus coupled with the intense solar radiation make it a particularly interesting system to study. One intriguing aspect of the photochemistry of Venus is the creation and destruction of free oxygen.

In Venus' upper atmosphere ultraviolet light from the sun splits carbon dioxide molecules into carbon monoxide and atomic oxygen (O). The direct recombination reaction to produce carbon dioxide from carbon monoxide and atomic oxygen is very slow so the majority of this atomic oxygen forms O_2. The 2O to O_2 reaction emits a characteristic light which forms an airglow that is visible on the dark side of Venus. By measuring the intensity of this glow scientists can estimate the rate of molecular oxygen production. "We know the rate of oxygen generation on Venus is quite high from the airglow data," Dr Mills explains, "but when we look at the bright side of Venus using absorption spectroscopy we see very little molecular oxygen. So some process has to be consuming it at a very fast rate. Our current models can't really plausibly explain this so it's an area of great interest to planetary scientists."

Venus is sometimes termed the Earth's twin due to its almost identical size, its similar proximity to the sun, and the likely (but not yet proven) similarities in its initial composition. The Earth's first stable atmosphere was dominated by carbon dioxide, much like Venus today except not nearly so dense. Over the course of billions of years, the evolution of life on Earth transformed the atmosphere by releasing free oxygen and binding the CO_2 in biomass and sedimentary rocks. "In a sense you can think of the early Earth as being quite Venus-like." Says Dr Mills, "It would be unfortunate if the Earth turned back to that state!"

Understanding how to prevent that happening has been a primary objective of climate scientists. A very important step in doing so has been to develop models of atmospheric processes so thorough and reliable that no one can question the need to take heed of their future predictions.



Artist's impression of Venus Express in orbit around Venus. Image: European Space Agency

THE AUSTRALIAN NATIONAL UNIVERSITY

ScienceWise is published by the
Australian National University
Editor: Dr Tim Wetherell

Subscription

Subscription to ScienceWise is free to schools, if you would like to be added to our lists please visit

http://sciencewise.anu.edu.au

CRICOS Provider No.00120C

ScienceWise
offsets its paper consumption with contributions to native tree planting programs.