CSEM's
Materials Monthly

May 2006
Making materials matter

New light on the dark side of matter

CAMS and working with positrons

To make sure that Australia captures the benefits of antimatter research an ARC Centre of Excellence devoted to antimatter-matter studies has been established. Known as CAMS – the Centre for Antimatter-Matter Studies – it's hosted by the ANU and includes other universities and government laboratories, and promises to raise the status of antimatter from something obscure and abstract to something real and now.

Mention antimatter in public and it'll be assumed you're either a sci fi fan or a theoretical boffin. That's because most people see antimatter as an abstract concept with little place in the real world. And yet the truth is a bit different – antimatter is a commonly used substance with many important applications. PET scans, for example, are a common form of diagnostic imaging used to dectect tumours and it works by releasing antimatter in our bodies. Firing antimatter at the surface of materials, as another example, is a technique for characterising those surfaces. Indeed, antimatter plays a number of roles in the real world and its value in materials science, medicine and biology is only set to increase.

So what is antimatter?

"As the name implies, and as most people would have heard, antimatter is the same as normal matter but with an opposite electrical charge," says Professor Stephen Buckman, Research Director of CAMS. "Antimatter electrons are identical to normal electrons but carry a positive charge where normal electrons carry a negative charge. Antimatter protons are negative where normal protons are positive. Indeed, it's believed there's an antimatter equivalent for each of the known subatomic particles.

"If an antimatter particle comes in contact with a normal matter particle they annihilate and are converted into energy. The amount of energy released is predicted by Einstein's equation: $E = mc^2$; where m is the mass of the particles and c equals the speed of light. That energy is released in the form of gamma rays."

And therein lies the reason why antimatter is considered so exotic, so 'other wordly'. If it comes into contact with normal matter it dissapears in a burst of gamma rays so how can it serve any useful function in a world made from normal matter?

"There's no question that antimatter is an exotic substance and it's not easy to work with but there's a lot more to it than abstract physics," says Professor Buckman. "When antimatter meets normal matter it takes only a split second before its gone but in that split second of interaction it's possible

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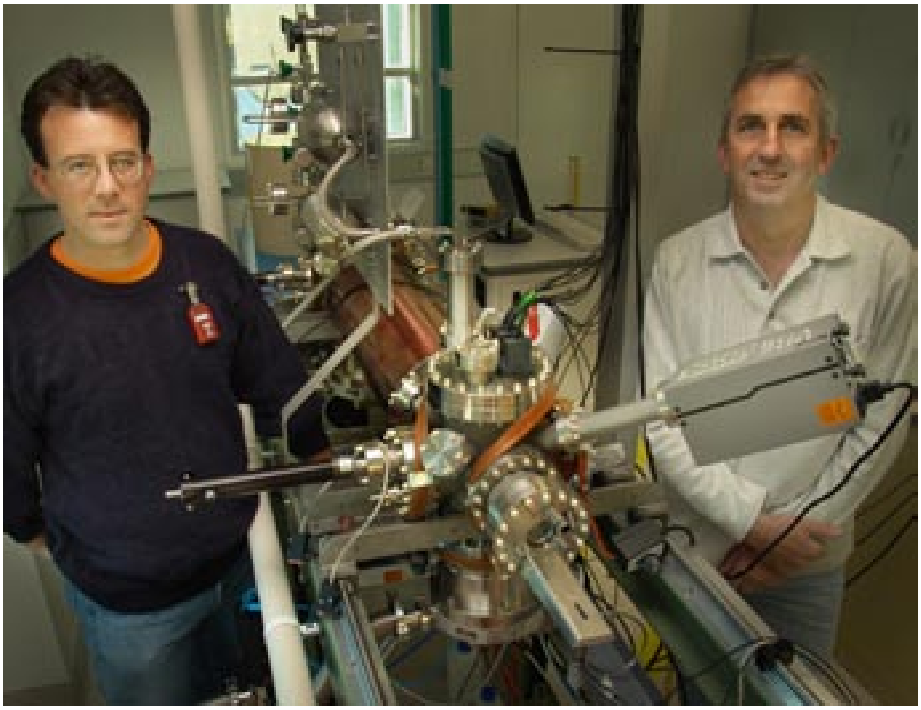

Professor Stephen Buckman (right), Director of the Centre for Antimatter-matter Studies (CAMS) with Dr James Sullivan. The two scientists were responsible for the design and construction of the positron beamline. (Photo by Tim Wetherell)

Antimatter-matter research

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to learn a lot about the physical environment around the antimatter particle.

"On top of this, when antimatter annihilates with a normal matter particle, gamma rays are released. Gamma rays are easily detected allowing researchers to pinpoint where the antimatter-matter particle pair was when it disappears. These particles are too small to see with any microscope but when they annihilate the gamma rays they give off are a crystal-clear signal that is easy to pick up. These aspects of the interaction between antimatter and matter lend themselves to some very useful applications in the areas of medical scanning, materials characterisation and theoretical particle physics."

If antimatter can't coexist with normal matter for more than an instant and our world is made of normal matter, where does it come from and how do you use it?

"There are two basic sources of antimatter on Earth," says Professor Buckman. "It's produced when subatomic particles collide, as occurs in particle colliders, and from the radioactive decay of some isotopes. Antimatter used in diagnostic scanning and materials characterisation uses antimatter produced by radioactive isotopes.

"The commonest form of antimatter used is the positron – the antimatter equivalent of the electron. Indeed, the positron is identical to the electron in all aspects except that it carries a positive charge."

Putting positrons to work

One of the most common applications of positrons is in medical imaging and PET scans. While many people have heard of these, few would connect them with antimatter, and yet PET stands for Positron Emission Tomography. The procedure involves injecting a patient with glucose containing a radioactive isotope, usually fluorine-18, which emits positrons. The body directs the glucose to areas of high metabolic activity, often indicating the presence of a tumour or some change causing increased blood flow or immune system activity.

The fluorine-18 has a half life of a few hours. As it breaks down it emits a steady stream of positrons. These combine with electrons in the surrounding tissue, they annihilate and give off energy in the form of gamma rays. The gamma rays are easily detected and allow the source of the increased metabolic activity to be mapped, usually down to a resolution of 2-3mm.

"PET scans are a well-developed diagnostic tool and yet little is known about how positrons interact with biomolecules despite the sophistication and cost of the technology," says Professor Buckman. "One of the aims of CAMS is to study the interaction of positrons with bio-molecules and try and shed light on what happens between positron emission and positron annihilation. In particular, we want to look at ways in which the efficiency of the process might be improved. In so doing we think we can improve the resolution of PET scans."

Positrons are also a useful tool in the analysis of materials. When positrons are fired into a material they tend to drift towards any open volumes — very small holes. This is because they like to be away from the positive charge of the fixed nuclei in the material — like charges repel. When it finds a hole in the material, there are no electrons to annihilate with, so the size of the hole determines how long the positron lives.

"By looking at the lifetime of the positrons in the material, we can get information about the size and distribution of holes, or defects, that are as small as a nanometre in size," Says Professor Buckman. "Holes of this size are related to important properties in some materials, such as porosity and conductivity. They can also be an early indicator of material degradation. In CAMS we plan to use one of the positron beamlines for the study of materials for various applications, from new generation plastics to silicon wafers.

Crossing to the dark side

Professor Buckman's interest in positrons and antimatter arose from his earlier research on electrons. He says it's not an enormous jump to switch from electrons to positrons.

"Several years ago I spent some time over at the University of California, San Diego, where they have a beamline set up specifically for the study of positrons," he explains. "When I saw what they were achieving over there I realised that antimatter science was a real opportunity for us in Australia because our strengths in electron atomic physics meant we already possessed the core expertise to undertake these studies. You might say my exposure to this positron research convinced me it was worth crossing over 'to the dark side'.

"When I returned to Australia I got in contact with several research groups around the country with an interest in antimatter and we were successful in obtaining funds in 2004 from the

Thinking up antimatter

Antimatter is a good example of science predicting the existence of something before it's actually observed (or even suspected). In 1928 the British physicist Paul Dirac combined quantum theory and special relativity in one equation in an effort to better model the behaviour of electrons. His solution, known as the Dirac equation, worked exceptionally well describing many attributes of electron motion that previous equations could not. However, it also suggested the possibility of the existence of electrons with positive charges – anti-electrons. But where would you look to find such a strange beast?

The existence of anti-electrons created a real problem for the growing field of quantum physics. Everyone accepted the mathematics of Dirac's equation but anti-electrons did not correspond to anything known in the physical world. Werner Heisenberg, one of the world's leading quantum physicists at the time, initially called this "the saddest chapter of modern physics". However, as events were soon to demonstrate, it was to end in intellectual triumph.

Four years later when studying the particle tracks left by collisions with cosmic rays a particle was identified that had the same mass as an electron but the opposite charge – the anti-electron or positron had been found.

Since then it's been determined that an antiparticle exists for each of the known sub atomic particles and that these are naturally generated by cosmic rays impacting with normal matter. Amidst the cascade of resulting particles antiparticles will often result, existing for nanoseconds before combining with normal matter and annihilating.

In 1933 Dirac (pictured below) was awarded a Nobel Prize for his modelling of the electron and prediction of antimatter. He was just 31 years of age.

Australian Research Council to build a low energy positron beamline here at RSPSE.”

The funding, which amounted to around $1million, was part of the ARC National Facilities program. The other partners in the project were Griffith University, Flinders University, Charles Darwin University and CSIRO.

“In the couple of years that it has taken us to build the low energy beamline we’ve discovered there’s a lot more interest in antimatter-matter studies around the country than we first realised,” explains Professor Buckman. “To capitalise on this interest and the diverse range of skills available around the country the original concept has been expanded with an ARC Centre of Excellence grant worth $7 million over five years. In addition to this the institutions involved are chipping in an extra $3 million. This funding will enable us to build an additional high energy beamline which will greatly enhance our capacity for positron studies on materials.”

And the beamline is the key to studying positrons as it allows you to control the energy of the positrons and precisely measure its interactions with matter.

A beam of positrons

The source of the positrons in the CAMS beamlines is a tiny speck of radioactive sodium 22. It’s a only a few nanograms in size, so tiny that you can’t see it with the naked eye. It was produced by a nuclear reactor in South Africa, the only place in the world capable of creating this isotope, and costs around US$25 thousand.

“That would make it the most expensive material I’ve ever worked with,” observes Professor Buckman.

And, if you do the sums, he’s not joking. A gram of this material, about the size of pill, would cost billions of dollars.

Fortunately, for CAMS’ purposes, a few nanograms is all they need. Sodium 22 has a half life of around 2.6 years meaning this solitary speck can supply their beamline with a serviceable number of positrons for around three to four years.

The sodium sits in a lead lined chamber at one end of the beamline. It emits around a billion positrons every second, firing them off in all directions and with a wide range of energies. Most of the positrons have energies that are too high to be of practical value so before they enter the beamline they pass through a thin film of solid (frozen) neon. Around 1% of the positrons make it through this step. These positrons are then confined in an electrostatic potential well where they cool to room temperature through collisions with nitrogen gas molecules. The positrons don’t combine with electrons of the nitrogen atoms because their energies are too low. This technique allows for the production of a high resolution beam.

When the trapped positrons have cooled sufficiently the beam is formed by carefully raising the confining potential and allowing the trapped positrons to spill out. This produces a very high resolution beam (with an energy width of around 25 meV) which can then be used for various experiments. The beam is confined in the radial direction by magnetic fields, while electrostatic potentials allow the positrons to be directed along the apparatus.

Positrons & materials

The materials side of the CAMS experimental program will be undertaken by ANU, ANSTO and the University of Western Australia. Each institution brings a range of experience in positron handling and materials characterisation.

“The goal of the materials research is to provide new tools for Australian scientists to investigate the properties of novel materials, such as polymers, thin films and semi-conductors,” says Professor Buckman. “It’s also hoped that our research and that of our collaborators, will be useful in the investigation of such properties as surface effects, fatigue in some metals and even for some medical applications.”

Three types of experiments in materials analysis are possible within CAMS: Positron Annihilation Lifetime Spectroscopy (PALS), Doppler measurements and surface studies.

PALS relys on the detection of 511 keV emitted gamma rays as a function of time elapsed from the entry of the positrons into the sample. The lifetime of the positrons in the sample changes as a function of various properties of the material, specifically on the presence of voids and defects. On entering the sample, positrons thermalise and either annihilate or form positronium with one of the target electrons.

Professor Buckman with the positron beamline. The cylinder on the right houses the radioactive sodium 22, the source of the positrons.

“Positronium is the substance formed when a positron and an electron are bound together,” explains Professor Buckman. “In a normal atom, there is a heavy nucleus with a positive charge, with electrons orbiting around it. In the case of positronium, the positive nucleus is replaced by the positive positron. Positronium is really an exotic type of atom. It is very light and only lives for 120 picoseconds or 142 nanoseconds, depending on the configuration of the electron and positron. The key to these studies is understanding the formation and annihilation of positronium.”

The stuff of sci fi

One of the reasons antimatter has such as an exotic aura is its frequent use in science fiction as a source of seemingly unlimited energy or as a weapon. Mix a little antimatter and normal matter and their combined mass is converted to massive amounts of pure energy. It sounds pretty appealing, and has been the driving force behind the Starship Enterprise since the inception of Star Trek. However, it overlooks the fact that antimatter is very, very expensive to create. To produce a single gram of sodium 22, the radioactive isotope used by CAMS to produce positrons, you’d need about twice the GDP of the United States (as measured in 2004).

Positronium can be formed in two configurations: para- and ortho-positronium (the singlet and triplet form of the positronium ground state, respectively). Para-positronium decays via 2-gamma emission (with both gamma rays having an energy of 511 keV) with a lifetime of 120 ps. Ortho-positronium, on the other hand, decays via 3-gamma emission with a lifetime of 142 ns. However, inside a solid material the lifetime of ortho-positronium depends on how easily it can annihilate via ‘pickoff’ annihilation, where the positron annihilates with one of the other electrons in the

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Slivers away

Thinking outside the square = thinking inside the wafer

Few industries can boast a sustained growth rate of 23% but that's just what's been happening in the photovoltaic (PV) industry over the last 15 years. And that growth is set to continue as an energy hungry world searches for alternatives sources of electricity (23% was an average growth rate; the PV industry grew by 65% in 2004!). However, the PV industry is facing a major challenge in the form of a critical shortage of hyper-pure silicon at an affordable price.

Solar cells are traditionally made from wafers of hyper-pure, crystalline silicon (see box on how this is produced). These wafers – typically 15 cm in diameter and less than half a millimetre thick - are used in 95% of photovoltaic modules. The shortage of hyper-pure silicon is proving a major barrier to reducing the price of PV-based energy, and it's a shortage that only promises to grow over the next decade.

There have been many attempts to get around this bottle neck. Some have involved using non-silicon semiconductors based on materials such as gallium or indium, while others are based on using lower grades of silicon. However, none of these efforts have produced a solution that can compete with cells based on wafers of hyper-pure silicon in terms of cost per watt.

There's also been work on using thinner wafers of silicon but only incremental savings can be achieved here – you can only cut a traditional wafer so thin and there are significant losses of silicon in the process of slicing up the original ingot of silicon into wafers.

But researchers at the ANU Centre for Sustainable Energy Systems (CSES) have found a way around the problem and their solution lies in a little lateral thinking and a lot of clever materials engineering. The lateral thinking involves cutting thin layers of silicon out of the wafer itself. The clever materials engineering is how they achieved it.

"The main issue we needed to tackle was how to reduce the amount of high grade silicon being used in solar cells," says Dr Klaus Weber from the CSES. "We knew that simply cutting the silicon wafers thinner would only produce incremental improvements and we were looking at more than merely improving what we already had. So, we began to think outside of the square or, for this problem, inside of the wafer. It occurred to us that maybe we should be working with the volume of the wafer rather than with its surface."

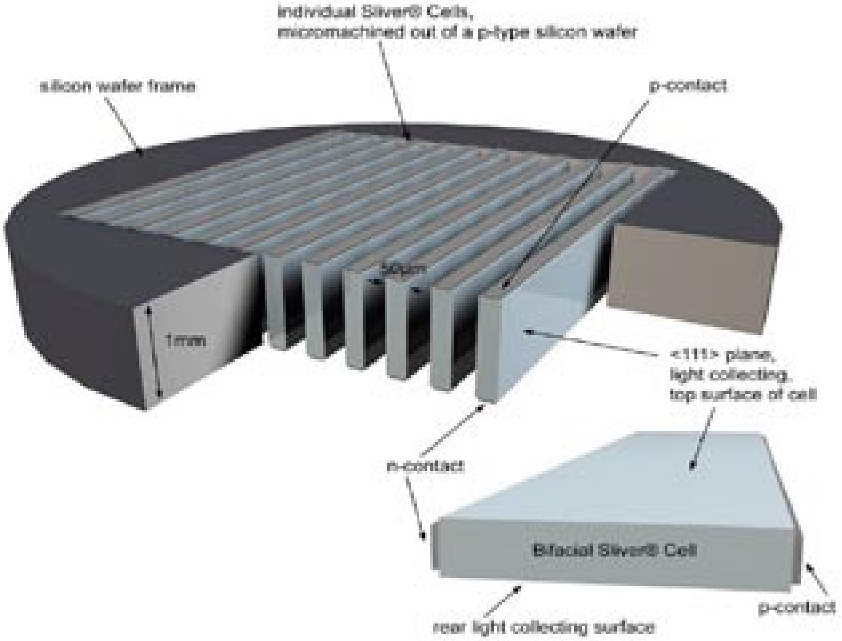
What they did was cut narrow grooves into the silicon wafer using an alkaline etch. The alkaline etch attacks most of the silicon quickly but the (111) crystal plane slowly. A resistant mask is placed on the surface of the silicon wafer. The mask has long narrow slots cut into it. The silicon below the mask is oriented such that a (111) plane is perpendicular to the wafer surface. Etching commences at the surface of these narrow slots and continues down through the entire thickness of the wafer. The result is a large number of thin silicon strips in the centre of the wafer, held together by the unetched surrounds of the wafer.

In effect the wafer has been cut into a series of slivers, with each sliver approximately 50-100mm long and 40-60μm thick. Each sliver is as wide as the wafer is thick and the researchers found that the process was most efficient using wafers that were 1-2mm thick.

The output of 72 conventional cells is the same as that from two wafers when the wafers are manufactured into Sliver® cells.

One important aspect is that after creating the grooves the slivers are still attached to the wafer. This allows the slivers to undergo further steps in the fabrication process before they are cut from the wafer. Each sliver is now an individual solar cell, and these are then assembled into modules.

Cells can be laid out with no gaps between them or with any spacing between slivers up to about 1.5 times the width of each cell. With a scattering reflector attached to the rear of each module, most of the



Silicon for solar cells

As materials go, surely there is no element as versatile and useful as silicon. After oxygen it's the most abundant element in the Earth's crust - it makes up a quarter of the planet's crust by weight. How is it then that hyper-pure silicon is in critically short supply for the manufacture of solar cells?

The silicon in solar cells is hyper-pure silicon, and making it is neither easy or cheap. It involves loading a crucible with high-purity silicon along with small amounts of either boron, phosphorus, arsenic or antimony (these impurities or dopants give the final product different electrical properties). The silicon is then melted at a process temperature of 1400°C in an atmosphere of pure argon. Once the proper 'melt' is achieved a 'seed' of single crystal silicon is lowered into it.

The temperature is then adjusted as the seed is rotated and slowly pulled out of the molten silicon. The surface tension between the seed and the molten silicon causes a small amount to rise with the seed. As the growing seed is pulled it cools to form a perfect single-crystal ingot with the same crystal orientation as the original seed. This ingot is then sliced up into individual wafers which are used as the basis of solar cells or integrated circuits.

light incident in the space between the cells can still be captured. Sliver® cells, as they are known, are truly bifacial as they respond equally well to light on either surface. They can be connected in any series and parallel configuration to deliver the output voltage required for any application.

So, how much hyper-pure silicon is saved using the Sliver approach? Consider this: A typical silicon wafer configured as a conventional solar cell will require about 10kg of silicon for each kilowatt of peak output power. However, a wafer, when processed to produce Sliver® cells, can achieve the same output with 1kg or less of silicon, which is 10 times better than for conventional technology. Moreover, far fewer wafers need to be processed to give the same output compared to conventional cells. The output of 72 conventional cells is the same as that from as little as two wafers when the wafers are manufactured into Sliver® cells.

As part of a research program substantially funded by Origin Energy, the Sliver process concept was invented by Dr Weber with Professor Andrew Blakers, Director of CSES, in 2000. Since then ANU's commercial collaborator Origin Energy has constructed a factory in Adelaide to produce Sliver® cells commercially. First sales occurred in July 2005 and full commercial production is expected to get underway later this year.

In the meantime, research at CSES is further improving Sliver technology. Recent results indicate that with careful engineering using well-known and established techniques, Sliver technology could reduce the costs of PV technology to the point where it will be competitive with wind energy and 'zero emission' coal. Given the vast worldwide solar energy resource, this has major implications for climate change policy.

More info: http://solar.anu.edu.au/ or email solar@anu.edu.au

Six strengths of the Sliver

1. More bang for your buck: Sliver® cells use approximately one tenth the amount of expensive silicon compared with conventional cells.

2. Designer transparency: any degree of module transparency can be easily achieved by adjusting the Sliver® cell spacing.

3. Flexible fitting: The thinness of the slivers makes them flexible meaning modules can be designed to flex and bend (opening up countless new architectural possibilities).

4. High voltage: Many Sliver® cells in series still take up very little area, so high voltages can be obtained in very small modules. This makes Sliver® cells ideal for powering small consumer items.

5. Bifacial response: The perfect bifacial response of a Sliver® cell means that Sliver modules respond equally well to light falling on either surface. This allows for novel applications of Sliver® modules. For example, highway round barriers can utilise Sliver® modules that are mounted vertically facing east-west.

6. Energy payback: The energy payback time of a Sliver® module is short because the quantity of energy-intensive silicon is sharply reduced. The energy payback time is 1.5 years, two thirds of which is due to standard module components (glass, aluminium frame etc.) compared with 4 years for a conventional module.

Antimatter-matter research

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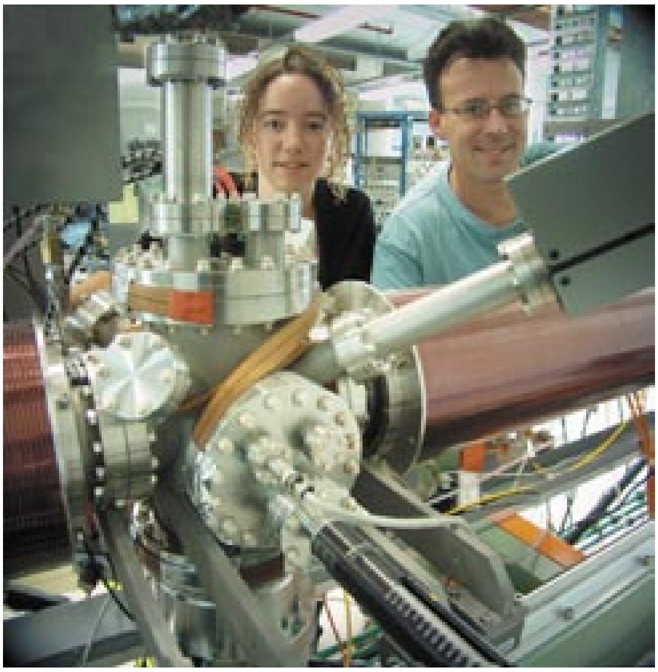
target (not the one it is bound to). The lifetime against direct annihilation is typically 100's of picoseconds.

If annihilation gamma-rays are detected as a function of time after entering the sample (usually the two 511 keV are detected in coincidence to improve timing resolution), then a series of lifetimes can be seen in the spectrum. These lifetimes give information about the structural makeup of the sample, and the ortho-positronium lifetime is particularly sensitive to the size and distribution of voids and defects. PALS, for example, has been used extensively by scientists at CSIRO to relate the average pore size in polymers to their oxygen porosity.



Dr James Sullivan, an ARC Research Fellow, and PhD student Ms Violaine Vizcaino by the positron trap. (Photo by Tim Wetherell.)

Doppler measurements provide additional information on the site of annihilation. Positrons that annihilate with a fast moving electron (ie, a core electron) will emit Doppler-shifted gamma rays. Measuring this shift can then provide information about the chemistry at the annihilation site. As positrons tend to be attracted to defects in the materials, this then gives us the ability to determine the chemical makeup at defect sites, such as voids, which may be sites for solute atoms forming clusters or precipitates.

Surfaces can also be studied using antimatter. Variable-energy, thermalised positrons will be scattered from thin films, surfaces and interfaces for metals, semiconductors and insulators, thereby yielding a range of information on the nature of the surface.

Two beamlines

“The high energy beamline being built at CAMS will be dedicated to materials studies, ”says Professor Buckman. “This beamline will allow us to control the energy of the positrons being injected into the sample to be tuned up to 20 keV. This will allow the samples to be probed as a function of depth, and we can go into the sample to approximately 1 micron.

“Our existing low energy beamline has a peak energy of 100 eV. This is suitable for investigating biological systems and fundamental atomic and molecular interactions with positrons.

“The fundemental investigations involve understanding the interactions of positrons with atoms and molecules in a way that gives us insight into their behaviour at a quantum mechanical level. Despite that fact that quantum mechanics has been around for a long time the interactions of positrons with single atoms is notoriously difficult to model correctly. Instead, numerous approximations have to be made to describe the interactions and a lot of computing power is needed to solve the equations numerically. The facilities of CAMS will allow the experimental investigation of these interactions at an unprecedented level of accuracy. In addition, CAMS includes some of the best theorists in the world in this area. By combining experiments with a new theoretical understanding, we expect to greatly increase our understanding of the interactions of positrons and matter at a fundamental level.”

Partners in antimatter-matter research

CAMS is hosted by ANU and has a total of 15 collaborating partners. Australian members are Flinders, Murdoch and Griffith universities, the University of WA, and ANSTO. Overseas partners are The Open University, The Universities of California in San Diego and Davis, The Lawrence Berkeley National Laboratory, Drake University, the University of Nebraska, Tohoku University, and the University of Munster.

The design of the two beamlines are based on a positron beamline operated by the University of California, San Diego, though many aspects of these new facilities are unique to Australia.

“Our two beamlines incorporate a lot of second generation improvements to the technology,” says Professor Buckman. “We will have a more intense beam with a broader program of study.

“This Australian facility will place us at the global forefront of positron physics. There is no other centre in the world with such an adventurous focus or such a breadth of activities involving positrons.”

The high energy beamline is scheduled to be operating by the end of this year.

More info: www.positron.edu.au or email Professor Buckman <Stephen.Buckman@anu.edu.au

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