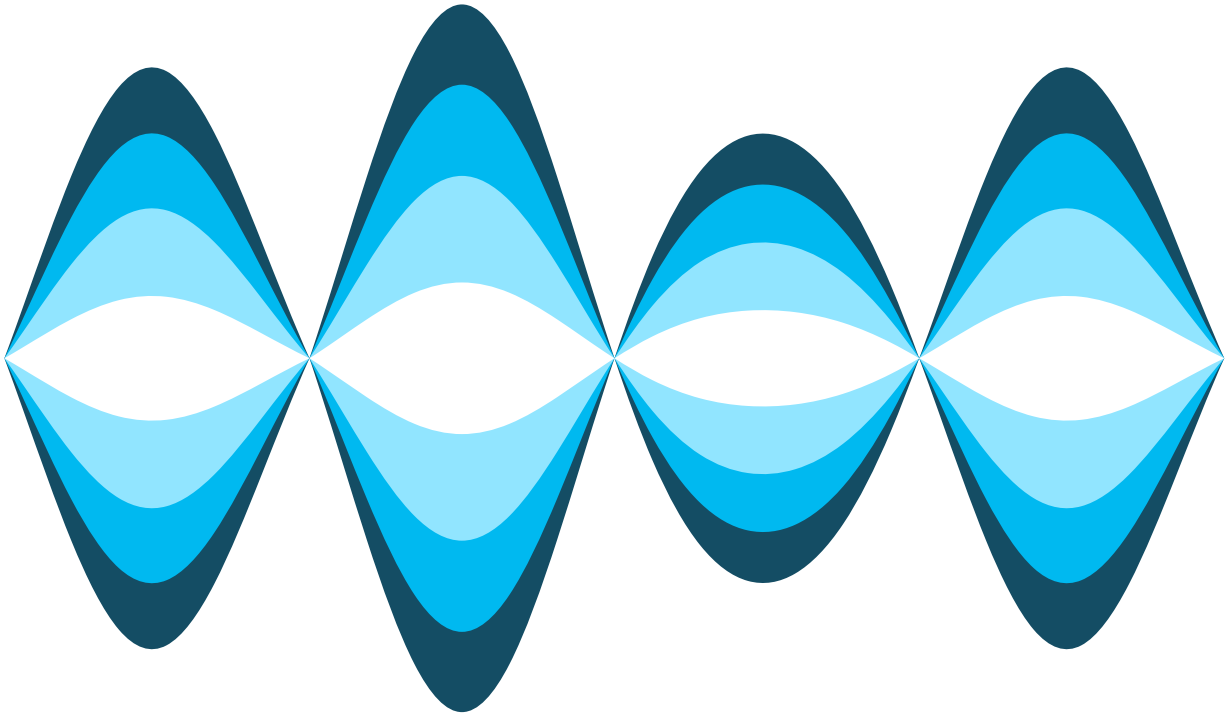

Heavy Ion Accelerator Symposium 2018

Book of Abstracts and Program

Heavy Ion Accelerator Symposium 2018 Schedule

Monday 19th		Tuesday 20th		Wednesday 21st	
08:30-09:00	*Registration*				

Session 1		Session 5		Session 9	
09:00-09:10	K. Kirk	09:00-09:30	M. Penniment	09:00-09:30	N.M. Strickland
09:10-09:40	A. E. Stuchbery	09:30-09:55	C. Notthoff	09:30-09:50	G. Biasi
09:40-10:10	R. Bartley	09:55-10:20	E.C. Simpson	09:50-10:10	J. Murray
10:10-10:30	H. Rutherford			10:10-10:30	S. Bakr
10:30-11:00	*Morning Tea*	10:20-10:50	*Morning Tea*	10:30-11:00	*Morning Tea*

Session 2		Session 6		Session 10	
11:00-11:30	Z. Pastuovic	10:50-11:20	Q. Hua	11:00-11:30	M. Safavi-Naeini
11:30-11:50	S. Bakr	11:20-11:45	A.M. Jakob	11:30-11:50	J. Allen
11:50-12:10	P. Reid	11:45-12:10	P.P. Murmu	11:50-12:10	P. Mota-Santiago
12:10-12:35	U. H. Hossain	12:10-12:30	P. Medley	12:10-12:35	J. S. Laird
12:35-13:30	*Lunch (NP)*	12:30-13:30	*Lunch (NP)*	12:35	*Conference Closes*

Session 3		Session 7	
13:30-14:00	L. T. Tran	13:30-14:00	D. S. Geoghegan
14:00-14:30	J. C. McCallum	14:00-14:25	S. Guatelli
14:30-14:55	M. Vos	14:25-14:50	S. Pavetich
14:55-15:25	*Afternoon Tea*	14:50-15:20	*Afternoon Tea*

Session 4		Session 8	
15:25-15:55	A. Hadley	15:20-15:50	Y. Yokoyama
15:55-16:15	B. Tee	15:50-16:10	Y. Wu
16:15-16:35	D. Bolst	16:10-16:35	R. Elliman
16:35-17:00	I. P. Carter	16:35-16:55	A. Kiy

17:00	*Talks End*	16:55	*Talks End*
17:15	*Dinner (NP)*	17:15	*HIAF Tours*
19:00-20:00	*Public Lecture*	18:00	*Dinner (NP)*

Registration and all tea breaks will be held in the foyer of the John Curtin School of Medical Research, just outside the Finkel Lecture Theatre. Lunch and dinners will be held at the Department of Nuclear Physics (NP), which is a short walk from the Finkel Lecture Theatre.

Contents

Welcome

Welcome to the 2018 Heavy Ion Accelerator Symposium and to Canberra.

This is the sixth edition of the series of symposia instituted by the Department of Nuclear Physics at the Australian National University. The theme of this year's Symposium is 'Applications of Accelerated Ions', with particular focus on:

- Accelerator applications in Materials Science;
- Applications of nuclear isotopes in environmental processes;
- Ionising radiation in Biology and Medical Science.

The program of talks illustrates the diverse range of active research activities in our region, and the strong prospects for growth. We hope that, by bringing together experts from across the nation, and beyond, the Symposium can serve as a forum for building cross-institutional and interdisciplinary links in research areas exploiting using heavy-ion accelerators and associated state-of-the-art instrumentation.

The local organisers are especially grateful for the support provided by the Australian National University and the Research School of Physics and Engineering in organising the conference, and to the Australian Institute for Nuclear Science and Engineering for their support of travelling students.

If you need any assistance during the meeting, please speak to any of the local organisers or our Departmental Administrator, Petra. Contact details are provided below, and details of how you can access the Wi-Fi network are provided on the back of your name badge.

We hope for interesting and productive discussions during the week, and we wish you an enjoyable time at the Symposium.

Michaela Froehlich, AJ Mitchell and Ed Simpson
Co-chairs, Heavy Ion Accelerator Symposium 2018

Code of Conduct

The Heavy Ion Accelerator Symposium 2018 is dedicated to providing a positive respectful conference experience for everyone regardless of their gender, gender identity and expression, sexual orientation, disability, physical appearance, body size, race, age, socio-economic background or religion. We welcome diversity and recognize that the Symposium is better for it. We want to provide an environment that is free from discrimination, vilification, harassment, bullying and victimisation and characterised by respect. **Therefore, we do not tolerate harassment of Symposium participants in any form.** Sexual language and imagery is not appropriate at any time during the conference, including talks. Symposium participants violating these rules may be sanctioned or expelled from the conference (without a refund) at the discretion of the conference organisers.

Harassment includes: offensive verbal or written comments (related to gender, gender identity and expression sexual orientation, disability, physical appearance, body size, race, religion); sexual images in public spaces; deliberate intimidation; stalking; following; harassing photography or recording; sustained disruption of talks or other events; inappropriate physical contact; and unwelcome sexual attention including harassment by electronic (and social) media. Participants asked to stop behaviour considered as harassing are expected to comply immediately.

All attendees are subject to the *Code of Conduct* policy. All presenters should ensure that they do not use sexualized images, activities, or other material.

If a participant engages in harassing behaviour, the Symposium organizers may take any action they deem appropriate, including warning the offender, cutting short their presentation or expulsion from the conference. If you are being harassed, notice that someone else is being harassed, or have any other concerns, please contact one of the conference organisers immediately.

The organisers will be happy to help participants contact police, provide escorts, or otherwise assist anyone experiencing harassment to feel safe for the duration of the Symposium.

We value your attendance and appreciate your active support in making our Symposium inclusive.

Contact details:

Email address for organisers: hias@anu.edu.au
ANU Security: 02 6125 2247
Local police: 02 6256 7777
For all emergencies please call: 000

We expect participants to follow these rules at all event venues and event-related social events.

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Conference Proceedings

The conference proceedings will be published in electronic form as a regular volume of the journal European Physical Journal Web of Conferences. All contributions will be peer-reviewed prior to being accepted for publication.

The deadline for submission of contributions to the proceedings is **31st January 2019**. The page limit for contributions is 6 pages. Guidelines and templates for the preparation and submission of contributions will be available on the conference website following the conference.

You should already have signed the appropriate copyright permissions form at the registration desk. If not, please contact a member of the local organizing committee.

Acknowledgements

The organisers are grateful for the support of the Australian National University and the National Collaborative Research Infrastructure Strategy (NCRIS) for providing administrative and financial support. We also are grateful for the support provided by the Australian Institute of Nuclear Science and Engineering (AINSE) for providing student travel support grants.

HIAS2018 Program

Monday, 19th November

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11:50	P. Reid	*The Role of the Human Papillomavirus in Head and Neck Cancers: Cancer Stem Cell Diversity and Response to Radiation.*	p34
12:10	U. H. Hossain	*Ion track morphology in fluoropolymers*	p22
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13:30 – 14:55	**Session 3**	**Chair: Rebecca Bartley**	
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14:00	J. C. McCallum	*The 5U Pelletron accelerator facility at The University of Melbourne*	p28
14:30	M. Vos	*Measurement of Auger electrons emitted after nuclear decay: the case of ^{125}I*	p30
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15:25 – 17:00	**Session 4**	**Chair: Dale Prokopovich**	
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16:35	I. P. Carter	*Millisecond Mineral Analysis using High Energy X-rays*	p24

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19:00-20:00 **Public Lecture**

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Abstracts

Ultra-Low-Noise Detector Technology for Donor-Qubit Architecture Engineering and High-Resolution RBS Analysis

A.M. Jakob[1,3], B.C. Johnson[1,3], S.G. Robson[1], D. Holmes[1], J.C. McCallum[1,3], V. Schmitt[2,3], V. Mourik[2,3], A. Morello[2,3] and D.N. Jamieson[1,3]

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[2] *Electrical Engineering and Telecommunications, UNSW, Sydney, NSW 2052 Australia*

[3] *ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC²T), Australia*

The remarkable success in addressing and manipulating single P-donor spins ("qubits") in ^{28}Si [1,2] represents a milestone for the realisation of silicon-based quantum-computing. Inspired by these results, innovative P-donor quantum architectures were recently proposed [3]. Successful multi-qubit entanglement will depend on development of protocols that allow the engineering of well-defined shallow donor-qubit arrays. Furthermore, the elimination of disturbing background spins ("spin vacuum") via isotopic enrichment with ^{28}Si is crucial to ensure a robust qubit-ensemble control.

The proposed new architectures pose new challenges for ion implantation. The challenges range from the deterministic engineering of ordered ultra-shallow donor arrays with nanometre precision, to ultra-high fluence implants ($>10^{18}$ cm^{-2}) for local isotopic ^{28}Si purification with negligible impurity introduction.

With regard to the first challenge, our ongoing development of ultra-low-noise detector electronics has yielded a number of key achievements. We present single ion detection performance at room temperature for 14 keV P^+ ions and address the employment of heavy PF_3^+ molecule-ions to enable sufficient single ion detection fidelity of sub-10 keV ions. This ability constitutes a major step towards upscale-compatible donor-qubit placement with sub-10 nm spatial precision.

A modified configuration of this detector setup allows RBS measurements with an energy resolution below 5 keV for 1 MeV He^+ probe ions. We apply this technique to monitor the isotopic enrichment and impurity introduction in silicon for $^{28}Si^+$ and $^{28}Si^-$ implant fluences above ~4×10^{17} cm^{-2}.

[1] J. Pla et al., Nature 489, pp. 541-545 (2012)
[2] J. Pla et al., Nature 496 (2013)
[3] G. Tosi et al., Nat. Commun. 8, 450 (2017)

In situ small-angle x-ray scattering measurements of ion track etching in polymers

A. Kiy[1], M. Grigg[1], C. Notthoff[1], A. Hadley[1], U. H. Hossain[1], P. Mota-Santiago[1], N. Kirby[2], and P. Kluth[1]

[1] *Department of Electronic Materials Engineering, Research School of Physics and Engineering, Australian National University, Canberra ACT 2601, Australia*

[2] *Australian Synchrotron, ANSTO, Clayton VIC 3168, Australia*

When a highly energetic heavy ion passes through a target material, the damaged region left in its wake often exhibits preferential chemical etching over the undamaged material. This etch-anisotropy can be used to create very high aspect ratio channels (pores) of up to tens of microns in length, with pore diameters as small as several nanometres. Membranes formed by this method are ideal for many advanced applications including ultra-filtration, bio- and medical sensing, nano-fluidics, and nano-electronic devices. The shape of the etched pores can be cylindrical, conical or double conical, depending on the etching conditions. One major advantage of the technique is the ability to generate arrays of pores that are highly parallel with extremely narrow size distributions.

The aims of this research are to develop a detailed understanding of the track etching process and the etching kinetics in polymers by performing *in situ* small angle x-ray scattering (SAXS) measurements during the etching process. The SAXS measurements were carried out at the Australian Synchrotron in Melbourne, Australia. Investigating the influence of etching parameters and pore areal density on nano-pore formation enables the controlled fabrication of nano-pore membranes with size and shape-specific pores. For our experiments we used 12 µm thick foils of PET and 20 and 30 µm thick polycarbonate (PC) foils, irradiated with 2 GeV ^{197}Au-ions at the GSI UNILAC in Darmstadt, Germany. The irradiated material was subsequently etched in diluted sodium-hydroxide (NaOH) at several concentrations and temperatures. The etching was conducted in a custom-built sample environment while performing the SAXS measurements in transmission mode to determine the track etch rate as a function of etch time. These *in situ* scattering images were analysed using a batch fit method to determine the pore size as a function of etching time. An example of a transmission SAXS scattering image of cylindrical pores in PC is shown in Fig. 1. The results of the study indicate that the track etching behaviour is strongly influenced by temperature and concentration of the etchant, whereas the pore areal density only has a small effect on the etch rate. This allows the calculation of activation energies for radial etching of PET and PC depending on their pore areal densities. The etch rates for PC are largely linear, however PET seems to have two etch rates indicating a damaged halo.

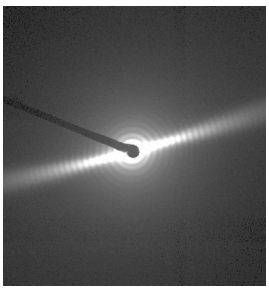

Fig. 1: Transmission SAXS scattering pattern from cylindrical pores etched in polycarbonate.

Characterisation of conical etched ion tracks in SiO_2

Andrea Hadley[1], Christian Notthoff[1], Pablo Mota Santiago[1], Umme Habiba Hossain[1], Stephen Mudie[2] and Patrick Kluth[1]

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[2] *Australian Synchrotron, ANSTO, Clayton VIC 3168, Australia*

When a highly energetic heavy ion passes through a target material, the damaged region left in its wake often exhibits preferential etching over the bulk. The etching process can create very high aspect ratio channels of up to tens of microns in length, with pore diameters as small as a few nanometres. Membranes formed by this method are ideal for many advanced applications including medical and bio-sensing, filtration and separation processes, nano-fluidics, and nano-electronic devices. The morphology of the etched channels can be cylindrical, conical or double conical, depending on the etching conditions. The resulting etched pores are highly parallel with very narrow size distributions.

The aim of this research is to develop a better understanding of the etching kinetics and the relationship between the un-etched ion tracks and the etched structures in SiO_2 to enable controlled fabrication of nano-pore membranes with size and shape-specific pores for applications such as bio and chemical sensors. 2 μm thin layers of SiO_2 were irradiated with 185 MeV ^{179}Au ions at the ANU Heavy Ion Accelerator Facility and with 1.1 GeV ^{179}Au ions at the GSI UNILAC in Darmstadt, Germany. The irradiated material was subsequently etched in diluted hydrofluoric acid at several concentrations. We have used small angle x-ray scattering (SAXS) in both transmission mode and grazing incidence to determine the track etch rate and cone angle as a function of etch time and etchant concentration. A full reconstruction of the scattering images enables detailed characterisation of the pore shape and size. An example of a transmission SAXS scattering image is shown in Fig. 1(a). A cross-section SEM image of the etched conical channels is shown in Fig. 1(b). The results of the study indicate that the track etching behavior is influenced by the ion energy, and that at short etching times the latent track damage in the radial direction becomes significant.

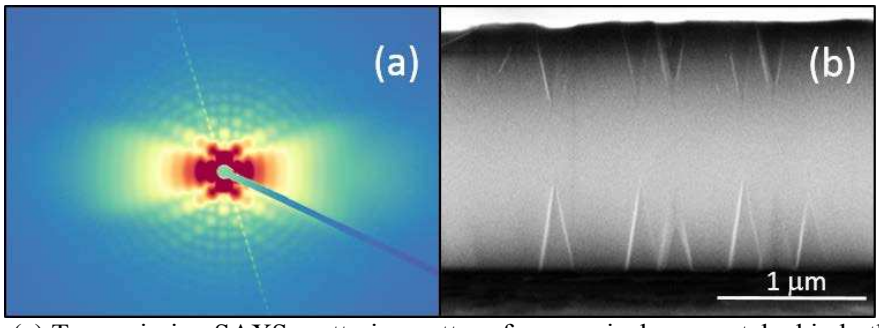

Figure 1. (a) Transmission SAXS scattering pattern from conical cones etched in both sides of SiO_2 membrane and (b) SEM cross section of etched ion tracks in SiO_2 membrane.

Experimental investigation of the conversion electrons from medical radioisotope ^{125}I

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^{125}I has potential to be used in a highly-targeted cancer therapy due to its specific decay characteristics, including the high number (up to 21) mainly low energy Auger electrons emitted following a single nuclear decay. These low energy electrons have a high linear energy transfer (LET) to the biological medium, and thus are suitable tools for such cancer treatment. However, in order to use the emitted Auger electrons for cancer tratment, the precise knowledge of the full energy spectrum of ^{125}I medical isotope is required. This knowledge is crucial to evaluate the radiation dose accurately.

^{125}I decays via electron capture to the 35.5 keV excited state in ^{125}Te. Due to its low energy, 93% of the time this excited state will decay via internal conversion to the ground state of ^{125}Te. In an internal conversion process, a core-hole electron is emitted from the radioactive atom, this electron is known as a conversion electron. Both the electron capture and the internal conversion will create atomic vacancies. The absolute number and distribution of these vacancies will control the Auger electron radiations. The 35.5 keV transition is known to be a mixed M1+E2 (magnetic dipole plus electric quadrupole) transition. Previous studies also indicated, that the M1 decay could also be affected by the so-called nuclear penetration effect.

Here we report on a new high resolution conversion electron measurement aiming to determine the degree of multipole mixing $\delta(E2/M1)$, as well as the penetration parameter λ, with precision. The measurements have been carried out using the ANU Electron Momentum Spectrometer (EMS) [1], operated at 5 eV energy resolution, which is more than an order of magnitude better, than any previous measurement of this decay. The monolayer ^{125}I source was prepared at ANSTO on a gold substrate, following the procedures described by Pronschinske et al. [2].

In this talk we will report on the new measurements and examine their impact on the Auger electron yield from the ^{125}I electron capture decay.

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[1] M.R. Went, M. Vos, J. Elect. Spec. and Rel. Phenom. **148** (2005) 107
[2] A. Pronschinske, et al., Nature Mater **14** (2015) 904

Swift heavy ion induced nano porosity in GaSb

Christian Notthoff,[1] Andrea Hadley,[1] Pablo Mota Santiago,[1] Umme Habiba Hossain,[1] Nigel Kirby,[2] Peter Kappen,[2] and Patrick Kluth[1]

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[2]*Australian Synchrotron, ANSTO, Clayton VIC 3168, Australia*

GaSb is a narrowband semiconductor, interesting for opto-electronic, photo-voltaic and thermoelectric applications. We have recently discovered the evolution of nano-porous structures in GaSb following swift heavy ion irradiation [1, 2]. Nano-porous semiconductors differ significantly in their physical and chemical properties from their bulk counterparts, due to their microstructure (see e.g. [3]). The controlled fabrication of porous semiconductors thus paves the way for the development of new materials with application specific properties. GaSb films with an initial thickness of 2 μm, grown on InP substrates as well as bulk specimens were irradiated with different fluences and incidence angles with 185 MeV Au ions at the ANU Heavy Ion Accelerator Facility. The resulting nano-porous GaSb samples are investigated using a combination of high resolution structural characterization techniques including synchrotron based small- and wide-angle x-ray scattering (SAXS/WAXS), extended x-ray absorption fine structure (EXAFS), as well as imaging (SEM) and optical measurements (Raman- and FTIR-spectroscopy). GaSb exhibits swelling, several times larger than the initial layer thickness. The figure below shows GaSb grown on InP irradiated with different fluences at 30° incidence angle. The microstructure of the porous material is highly dependent on the fluence as well as the incident angle of the ion irradiation. X-ray diffraction and Raman-spectroscopy reveal an amorphisation at low fluence, followed by a fluence regime where small (<10 nm) crystallites inside the pore walls are created. The results aid in understanding the processes operational during pore formation in GaSb.

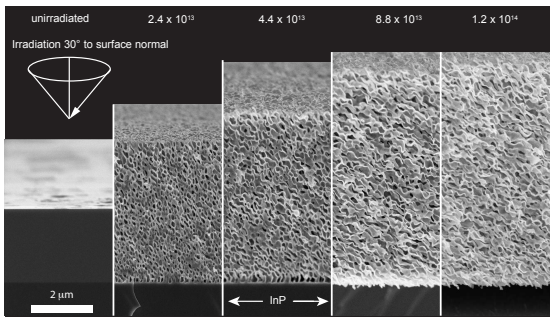

FIG. 1: GaSb film irradiated with 185 MeV Au ions at different fluences.

[1] P. Kluth, et al., *Appl. Phys. Lett.* **104**, 023105 (2014).
[2] C. Notthoff, et al., *Nuclear Inst. and Methods in Physics Research B* , in press (2017).
[3] L. T. Canham, *Appl. Phys. Lett.* **57**, 1046 (1990).

Performance of Geant4 for modelling silicon microdosimeters in heavy ion therapy

D. Bolst[1], S. Guatelli[1], L. T. Tran[1], L. Chartier[1,2], J. Davis[1], D. A. Prokopovich[1,2], A. Pogossov[1], M. I. Reinhard[1,2], M. Petasecca[1], M. L. F. Lerch[1], N. Matsufuji[3], M. Povoli[4], A. Summanwar[4], A. Kok[4], M. Jackson[5] and A. B. Rosenfeld[1]

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[2]*Ionising Radiation, NSTLI Nuclear Stewardship, Australian Nuclear Science and Technology Organization, Lucas Heights, NSW 2234, Australia*

[3]*National Institutes for Quantum and Radiological Science and Technology, Chiba, Japan*

[4]*SINTEF, Norway*

[5]*University of New South Wales, Sydney NSW 2052, Australia*

Heavy ion therapy (HIT) refers to the treatment of cancer with ions larger than protons. HIT offers many advantages over conventional photon radiotherapy including a more conformal treatment due to its well defined range and reduced scattering as well as a higher linear energy transfer (LET) which allow for better treatment of radio-resistant tumours. A large complication with HIT is that the relative biological effectiveness (RBE) of the beam changes drastically with energy, with a value changing from ~1 to ~3 at the Bragg Peak (BP). RBE is a measure of how effective a radiation type is at producing a biological effect and is vital to take into account its changing value when treating patients. An additional difficulty in HIT is the fragmentation of the primary beam with target nuclei, producing lighter fragments. These fragments have ranges which extend beyond the BP and laterally from the primary beam, transporting energy away from the treatment field to surrounding healthy tissue. It is critical to consider the effects of RBE and fragmentation and to confirm the delivered radiation field matches the planned treatment through quality assurance measurements.

Microdosimetry involves measuring the energy deposition spectrum in micron sized volumes and allows an estimation of the biological effect for any mixed radiation field. Conventional microdosimetry measurements are performed using tissue equivalent proportional counters (TEPC), traditional TEPCs suffer from a bulky size and complicated operation, these make them not well suited for routine quality assurance measurements. The Centre for Medical Radiation (CMRP) adopts solid state silicon-on-insulator (SOI) designs which address the shortcomings of traditional TEPCs.

In this study experimental measurements performed at the Heavy Ion Medical Accelerator in Chiba (HIMAC, Japan), using CMRP devices, are presented and compared to Geant4 (version 10.2p2). The microdosimeters were irradiated in ^{12}C, ^{14}N and ^{16}O beams with primary energies of 290 MeV/u, 180 MeV/u and 400 MeV/u, respectively. Comparisons between experiment and simulation yielded reasonable agreement between the two, demonstrating the favourable performance of the device. Downstream of the BP the energy peaks of fragments gave good agreement between experiment and simulation. However, in terms of the contribution of fragments it was observed that Geant4 produced an overabundance of lighter fragments compared to larger fragments.

Nuclear Reactions in Hadron Therapy

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Hadron therapy encompasses a new class of treatments for cancer where a beam of highly energetic protons or carbon ions is used to kill tumours. When charged particles pass through matter they deposit the majority of their energy at the end of their track, forming the Bragg peak. This gives hadron therapy two advantages over conventional radiotherapy: (a) a larger fraction of the dose is deposited in the tumour, sparing healthy tissue in the beam path, and (b) little dose is given to tissue beyond the tumour as the ions stop at the Bragg peak.

Worldwide there are 56 proton therapy and 10 carbon beam therapy facilities currently operating, with many more planned [1]. The first proton beam therapy centre in Australia is currently under construction at the South Australian Health and Medical Research Institute (SAHMRI) in Adelaide, and there are plans for a National Particle Treatment and Research Centre at the Westmead Precinct in Sydney.

One significant challenge in the planning of hadron therapy treatments are the nuclear reactions that occur as the beam passes through the body. In carbon beam therapy, up to 70% of the beam particles undergo a nuclear reaction before reaching the tumour [2], increasing the dose in healthy tissue, causing beam divergence, and creating a dose tail beyond the Bragg peak from low charge reaction products. These effects must be incorporated into treatment planning through careful modelling (often performed with GEANT4 [3]), requiring the total reaction cross section, and the energy and angle differential probabilities for all possible reaction products. A wide variety of nuclear reaction phenomena are possible over this range of energies, including inelastic excitation, nucleon knockout [4, 5], or fragmentation. Not only do we need to understand these reactions for the primary incident beam, but also for all the secondary reaction products produced. It is not feasible to measure all the reactions required, so models must be used.

Here we discuss ongoing work to improve the nuclear reaction models used in treatment planning, and consider what new measurements would optimally guide further progress. We will also discuss the potential and requirements for future measurements in Australia at the Bragg Centre, the proposed Westmead facility, and the Heavy Ion Accelerator Facility.

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Numerical characterization of a novel ΔE-E telescope microdosimeter on ^{12}C beam lines

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Successful radiotherapy treatments with ^{12}C depend on accurate knowledge of the mixed radiation field, contaminated by nuclear fragmentation, and of the radiobiological effectiveness (RBE) of the beam and its components [1]. One of the proposed methods to calculate the RBE_{10} is the microdosimetric kinetic model (MKM) applied to measurements of microdosimetric spectra [2]. Unfortunately, detectors able to characterize the radiation field with sub-mm resolution and simultaneously measure microdosimetric spectra are not currently commercially available.

One such proposed devices, is the silicon-based ΔE-E telescope (Politecnico di Milano, Italy) [3], a $25\ mm^2$ detector composed of a 1.9 µm thick ΔE stage and of a 500 µm thick E stage. In a previous study, it was reported that the device could be used to characterize the radiation field produced by a 290 MeV/u ^{12}C clinical beam at the HIMAC facility (Japan) with high spatial resolution, while simultaneously being able to measure microdosimetric spectra [4]. In that study, good agreement was found between experimental and numerical characterizations performed with a GEANT4 tool-kit.

In the present study, we report on the numerical modelling of the response of the ΔE-E telescope in a modulated (328.1 to 361.5 MeV/u) clinical ^{12}C scanning beam and in a low-energy monochromatic (5.95 MeV/u) ^{12}C beam. The first beam line was modelled after that at the CNAO facility (Pavia, Italy), while the second one was modelled after that at the 14UD facility at ANU (Canberra, Australia). The latter study is an important step in the quest for a comprehensive understanding of the side effects of particle therapy, its significance stemming from the information it provides on the fragments present in the distal part of the Bragg Peak. Simulations were performed adapting the application originally developed in [4], and adopting EM option 3 to model electromagnetic physics and QMD to model ion physics [5].
We show that, owing to its potential for distinguishing different fragments in a mixed radiation field produced by clinical and low-energy ^{12}C beams, the ΔE-E telescope can be used for sub-mm resolution measurements of microdosimetric spectra both in- and out-of-field. Spectra were obtained by correcting for tissue equivalence the energy distribution imparted in silicon, as recently suggested in [6]. In the future, numerical results will be compared to experimental data currently being collected.

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Ion track morphology in fluoropolymers

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The interaction of energetic heavy ions with materials can cause various structural and property changes. For example, when energetic heavy ions pass through polymer materials, they can create elongated damage regions of a few nanometres in width and up to tens of micrometres long called "ion tracks". The study of such ion tracks in polymer materials is a reseach field of current significant activity because of both its beneficial and detrimental aspects on materials modfication. Using the generally high susceptibility of the damaged material in the tracks to chemical etching, they have found various applications such as the production of nano-porous track-membranes for filters, micro-capacitors, diodes and nanowires for microelectronic devices and a large range of sensor applications. On the other hand, radiation damage may lead to unwanted degradation of their physical properties, e.g. in space applications or large scale particle accelerators.

Fluoropolymers are high performance polymers and show a very high resistance to solvents, acids and alkalis. A combination of interesting chemical and physical properties such as high mechanical and electrical resistance, thermal stability and low friction coefficient make them suitable for many hi-tech and biological applications e.g., as engineering plastics for aero-space industries, in optical and electronic devices and also as films or membranes [1, 2]. Several groups carried out experiments on chemical modifications of fluoro polymers exposed to protons, electrons, and ions. However, a detailed understanding of ion tracks morphology in fluoropolymers is still lacking.

Here, we investigate ion tracks in fluoropolymers e.g. polyvinylidene fluoride (PVDF), ethylene-tetrafluoroethylene (ETFE), tetrafluoroethylen-perfluoromethoxyethylen (PFA), and tetrafluoroethy-len-hexafluoropropylene (FEP). The tracks were created by irradiation with Xe ions of 1.1 GeV at the GSI UNILAC in Darmstadt, Germany, and Au ions of 185 MeV at the ANU Heavy Ion Accelerator Facility in Canberra, Australia at ion fluences between 2×10^8 ions/cm^{2}and 5×10^{10} ions/cm^2. The track morphology was characterised using small-angle x-ray scattering (SAXS) performed at the Austraian Synchrotron and structural changes were measured using Fourier-Transform Infrared Spectroscopy (FT-IR).

The average track radii and their dependence on the irradiation fluence and ion energy are compared and related to the individual polymer structure. The results show that the ion energy influences the size of the ion tracks. For samples irradiated with 185 MeV ions, the track size was significantly greater than for those irradiated with 1.1 GeV ions. However, track radii vary for different polymers showing the largest track radius (14.2 nm) for ETFE and the smallest track radius (4.5 nm) for FEP for identical irradiation conditions.

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Dose Quantification in Carbon Therapy using In-Beam Positron Emission Tomography

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Carbon therapy is a form of heavy ion therapy which uses a beam of accelerated ^{12}C ions to precisely deliver a therapeutic radiation dose to a target [1]. During carbon therapy, nuclear inelastic collisions between primary ions and target nuclei produce a range of fragments along the beam path, some of which are radioactive and decay via positron emission after their creation [1]. Positron Emission Tomography (PET) can be used to obtain the spatio-temporal distribution of positron annihilations in the target. Currently, most image-based quality assurance methods in carbon therapy compare the observed PET images to an expected activity distribution obtained from Monte Carlo simulations [2]. Direct quantification of the delivered dose from observation of the spatial distribution of positron-emitting fragments is difficult due to the complex physics of energy deposition and inelastic collisions [2]. In this study, a method for non-invasive *in-vivo* quantification of the dose distribution resulting from a poly-energetic ^{12}C beam is investigated in one dimension. A relationship between observed positron annihilations and the delivered dose was developed based on the observation that the spatial distribution of each positron-emitting fragment species is unique for each primary beam energy and target material. Linear independence of generated fragment distribution profiles with respect to beam energy between each of three homogeneous phantoms, and with respect to the phantom type for each energy, were established for experimental and Monte Carlo simulation data using cross-correlation and singular value decomposition. Fragment profiles produced by monoenergetic beams with a range of primary beam energies and target phantoms were used to perform factor analysis on activity profiles obtained following the delivery of a randomly-weighted poly-energetic beam, to estimate the proportional contribution of each energy. The calculated set of weighting factors describing the proportional contribution of each energy to the beam were found to be within 6% of ground truth, and subsequently the dose was estimated in the entrance, spread-out Bragg peak and dose tail regions to within 4% of the ground truth value.

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Millisecond Mineral Analysis using High Energy X-rays

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The rapid and accurate determination of the elemental concentration of minerals in ore is essential to ensure the maximum extraction of metals amongst decreasing ore grades worldwide. Gamma Activation Analysis (GAA) is one such method of non-destructive testing with the means to measure precious metals at parts per billion (ppb) levels [1]. GAA utilises high energy Bremsstrahlung X-rays produced by recently available high power electron accelerators to cause photo-nuclear interactions with target nuclei, inducing short-lived radioactivity in mineral samples. These excited nuclei return to their stable state through a series of gamma decays. The energies of these decays are known for a range of elements and can be used to accurately determine the concentration of the desired target element in the sample. GAA has already been experimentally verified as a highly accurate method of determining the concentration of gold through the ^{197}Au$(\gamma,\gamma')^{197}$Au-M reaction, with a half-life of 7.73 seconds [1]. This long lived 409 keV isometric state results in a strong 279 keV γ-ray emission which can be measured some seconds later away from the intense X-ray source, resulting in a relatively clean spectra free from residual short half-life activated background elements [1].

However, to improve the detection of gold concentrations in ores, it is also of interest to determine the concentration of arsenic as well, as this acts as an indicator for the presence of gold [2] and poses a disposal risk in larger quantities due to its high toxicity. Detection of arsenic through the same method applied for gold isn't possible as the meta-stable state of ^{75}As-M has a 17.6 ms half life. To measure arsenic, the detector array must be placed in close proximity to the X-ray source, directly exposing it to a extreme photon and neutron flux. This requires the use of fast, radiation hard detector with reasonable energy resolution. Recent developments in the growth of cerium-doped ceramic gadolinium garnet scintillator such as $(Gd,Y)_3(Al,Ga)_5O_{12}$ (GYGAG) [3] have the potenital to be suitable for this application. These detectors have previously been shown to be extremely hard to gamma radiation [3] but have yet to be exposed to a quantified neutron flux.

This presentation will discuss the challenges involved in operating the above mentioned novel scintillator in this radiation harsh environment, including the ability to measure γ-ray emissions from millisecond isomeric transitions..

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Validation of Geant4 Hadronic Nucleus-Nucleus Cross-Sections

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Simulating nuclear cross-sections aids in a range of physics research areas such as accelerator experimentation and medical radiation physics. Currently, the Glauber-Gribov model is used for calculating nuclear reaction cross-section in Geant4. The goal of the project is firstly to benchmark this cross-section model within Geant4 against experimental data from the EXFOR database. However, significantly more experimental data is required for accurate benchmarking for some cross-section systems such as those involving unstable heavy ions. We will present the first results of the project at the 2018 Heavy Ion Accelerator Symposium conference.

Defect Engineering in Graphene using Ion Irradiation

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The properties of 2D materials are sensitive to structural defects [1, 2]. Controlling the nature and concentration of defects therefore provides a means of tailoring material properties for specific applications. Ion irradiation is a well-established technique that provides a practical means of defect engineering, so there is particular value in understanding how the structure and concentration of defects depend on ion-irradiation parameters.

This study examines the effect of several important aspects of ion-induced radiation damage in graphene, namely: the effect of the ion fluence and nuclear stopping power (S_n) of incident ions on the concentration and structure of defects; the role of the substrate in damage production; and the significance of collective effects associated with molecular ion irradiation.

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Application of the Maia X-ray Detector Array on a Nuclear Microprobe

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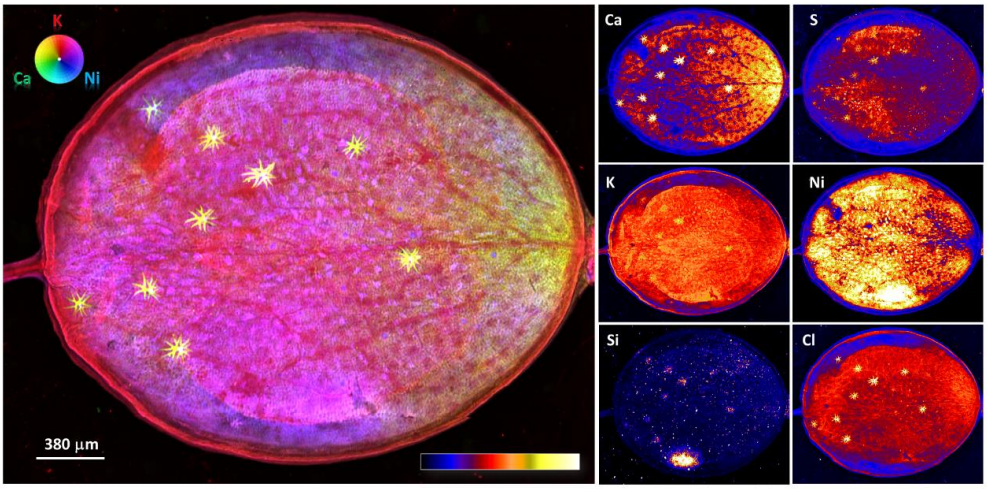
Trace element fluorescence imaging of materials has long been limited by the low throughput of energy dispersive detectors and their instrumentation chain. At higher count rates, spectral contamination from pulse pileup and deadtime effects severely limits trace element analysis and image fidelity. With the Maia detector however, an array of 20 x 20 (1mm [2]) pixels with a central hole results in a large detector solid angle of ~1.3 sr whilst spreading the resultant high count-rate amongst a massively paralleled detector instrumentation chain [1]. An onboard FPGA processes the resultant data using Dynamic Analysis (DA) [2] and streams real-time elemental maps across to the remote workstation for viewing. Raw data is stored on disk. Stage or electrostatic scans as well as scheduling is handled using the DAQ-36 system discussed elsewhere [3].

During the commissioning process, count rates approached ~10M/s or ~ 100 times higher than that used during normal PIXE analyses [4]. In this presentation we discuss the Maia detector implementation on the high excitation quintuplet Nuclear Microprobe at the University of Melbourne and explore its inherent strength to image at scale, in both geological and botanical samples where large area or wide field scans are necessary to better understand the processes at play. For example, shown below is an RGB composite image of an *Alyssum murale* seed capsule (1272 x 940 pixels) and individual element maps.



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The 5U Pelletron accelerator facility at The University of Melbourne

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The 5U Melbourne Pelletron is a single-ended National Electrostatics Corporation machine with three beamlines: the Melbourne microprobe, the CSIRO microprobe and an RBS/ion channeling line. Typical beams are He^+ or H^+ ions in the energy range 500 keV – 5.0 MeV. The accelerator facility is used for ion beam analysis and ion implantation. Analyses primarily utilise particle induced x-ray emission (PIXE), microbeam mapping and microanalysis, Rutherford backscattering spectrometry and ion channeling and nuclear reaction analysis. The accelerator supports the quantum computer development program of the Centre of Excellence for Quantum Computation and Communication Technology, diamond device and materials programs, SiC device and single photon source development and microanalyses related to mining and minerals exploration, botany and biosciences. A Maia x-ray pixel detector array has recently been installed on the CSIRO microbeam line. The detector array, with its large solid angle and parallel detection capability, enormously increases the microanalytical capabilities that are available. This presentation will provide an overview of the 5U Melbourne Pelletron facility and examples of recent analyses performed using the facility will be given to highlight the capabilities of the machine, the beamlines and accompanying instrumentation.

Recent development of solid state microdosimetry and its applications in particle therapy and space environments

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Particle therapy has many advantages over conventional photon therapy, particularly for treating deep-seated solid tumours due to its greater conformal energy deposition achieved by the Bragg peak (BP). Successful treatment with protons and heavy ions depends largely on knowledge of the relative biological effectiveness (RBE) of the radiation produced by primary and secondary charged particles. Similarly to heavy ion therapy, in deep space environments, where high energy heavy ions are observed, their linear energy transfer (LET) spectrum is important to be characterized and monitored due to their adverse effects on human health as well as electronic components. Microdosimetry involves the measurement of the energy deposition spectrum in micro-sized volumes and from this measured spectrum both the biological and electronic impact from the radiation field can be predicted.

Microdosimetric measurements are traditionally performed using tissue equivalent proportion counters (TEPCs). However, due to their poor spatial resolution they are not well suited to the sharp dose gradients associated with the distal edge of the BP. Additionally, due to their bulky size and complex operation make them challenging for onboard spacecraft use. To address the drawbacks of TEPCs, the Centre for Medical Radiation Physics (CMRP) has developed silicon-on-insulator (SOI) microdosimeters over many years. The latest CMRP SOI microdosimeters are called the “Bridge” and “Mushroom”, both have fully 3D micron sized sensitive volumes (SVs), mimicking the dimensions of cells.

The silicon microdosimeters provide extremely high spatial resolution and were used to measure the dose mean lineal energy and estimate the RBE_{10} using the microdosimetric kinetic model (MKM) for 290 MeV/u ^{12}C, 180 MeV/u ^{14}N and 400 MeV/u ^{16}O ions at Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan. The SOI microdosimeters have also been used to measure the LET of different ions with low energies at the ANU Heavy Ion accelerator including 52 MeV ^{7}Li, 70 MeV ^{12}C, 118 MeV ^{16}O and 170 MeV ^{48}Ti. The study of LET at ANU was to determine the applicability of silicon microdosimeters for high LET ions typical of space. Good agreement between the measured LET was observed with Geant4 and SRIM calculations. This confirmed that the CMRP SOI microdosimeters are not affected by plasma recombination up to LETs of approximately 1300 keV/µm in Si. The microdosimetric spectra obtained for low energy ^{12}C and ^{16}O ions were compared to the microdosimetric spectra measured at the distal part of the Bragg peak for therapeutic ^{12}C and ^{16}O ion beam that allows separate the contributions of the primary ion beam and secondaries.

The measurements performed over the years with the CMRP SOI devices have shown that they are well suited for characterising heavy ion therapy beam and for low energy heavy ions typical for space radiation environment inside of spacecrafts.

Measurement of Auger electrons emitted after nuclear decay: the case of ^{125}I

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During certain nuclear decay processes inner shell electrons are removed. In these cases the atom will relax from its initial, highly-excited state by emission of a number of X-rays and Auger electrons. Within the context of medical physics the Auger electrons are of particular interest as they deposit their energy in the close proximity of the emitting atom which could form the basis of targeted cancer therapy. Hence there is renewed interest in quantifying the number of Auger electrons emitted after nuclear decay. ^{125}I is used here as a case study, as it emits large quantities of Auger electrons and can be prepared as a monolayer source on a Au substrate which is stable for exposure to air.

For ^{125}I the energy of the Auger electrons varies from ≈ 25 keV to a few eV and quantitative measurement of their intensity is an experimental challenge, requiring a good understanding of the detector efficiencies [1]. We will present spectra taken with two spectrometers, that cover the whole range of energies and discuss how to derive from the measurement the number of Auger intensity emitted per nuclear decay and their energy distribution. A comparison is made with calculations using the BrIccEmiss [2] model for isolated atoms and the influence of the Au substrate on the emitted intensity and observed line shapes is discussed.

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The Australian Bragg Centre for proton therapy and research — plans for the future of radiation treatment of cancer patients and the opportunities for research

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The Australian Bragg Centre construction begins next year, however the planning for an integrated national particle therapy cancer treatment plan has already commenced. This includes comparative photon/ proton planning, a national MDT and clinical database leading to better decisions and data driven research. Clinical trial collaboration has begun with many overseas centres.

Non clinical research themes of biotech development, imaging, eye treatment and micro beam technology will be discussed along with discussion of how all the scientific community can engage and propose areas of research. There will be discussion on how we will assess projects for benefit to patients and the Australian Bragg Centre and how we can collaborate on business plans for proposals.

Enhanced flux pinning in HTS wires through ion-beam induced defects

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Columnar tracks created by heavy-ion irradiation are well known to be of ideal dimensions to contribute to magnetic flux pinning in high-temperature superconductors (HTS), thereby suppressing flux creep and enhancing the critical current (I_c). This enhancement is generally anisotropic relative to the orientation of an external magnetic field, relying on overlap of magnetic flux lines with ion damage tracks. Irradiation studies of HTS materials have historically focused on the ideal-overlap case (magnetic field in the same direction as the ion tracks) which highlights the physics of flux pinning. From an engineering point of view though, this ignores the effects on I_c when the magnetic field is applied in other orientations, as would inevitably arise in practical applications. When flux lines do not overlap ion tracks there is no enhanced pinning, and indeed I_c may be suppressed through the reduced superconducting volume fraction and/or widespread oxygen disorder. Disorder tends to reduce the superconducting transition temperature (T_c), amplifying I_c suppression at temperatures approaching T_c – in particular at 77 K, the most convenient characterisation temperature.

We have investigated the magnetic anisotropy of irradiated HTS wires at temperatures down to 20 K and fields up to 8 T. This provides for analysis of flux pinning anisotropy in different temperature and magnetic field regimes; we see in Fig. 1, for example, that a particular irradiation (185 MeV Au) is largely detrimental to I_c measured at (77 K, 1 T), but is significantly beneficial to I_c measured at (30 K, 3 T), a regime of importance to rotating machines applications [1]. This illustrates that ion energy and fluence should be tailored to the temperature and field intended for operation if the benefit is to be fully realised.

Annealing at 200°C to 500°C can partially restore suppressed I_c by re-ordering oxygen, while higher temperatures produce secondary phases leading to overall reduced I_c. An optimised post-irradiation anneal is therefore an important part of enhancing HTS wires by ion irradiation.

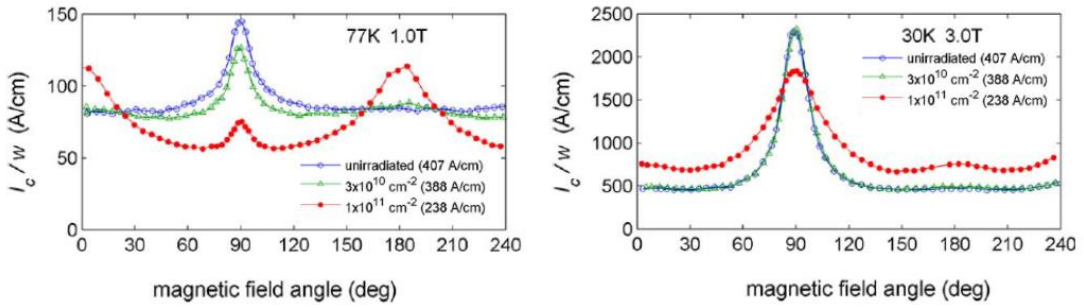

Figure 1. Critical current anisotropy of unirradiated and irradiated HTS wires at 77K, 1T and at 30K, 3T. At 77K, 1T there is a slight enhancement only near θ=0° or 180° (magnetic field aligned with ion tracks) while there is significant suppression of the I_c minimum. At 30K, 3T there is enhancement over a wide range of angles, and the I_c minimum is enhanced.

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Thermo-physical effects on ion-induced shape modification of gold nanoparticles in amorphous silicon nitride, silicon dioxide and at the interface between silicon nitride and silicon dioxide

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The design of metal-dielectric nanocomposites is of great interest because of their optical response that can be tuned by engineering the volume, geometry, orientation, metal species and the dielectric function of the surrounding medium. While many fabrication methods are available (among the most widespread are: chemical synthesis of metal colloids and core-shell particles, self-organization, electron beam lithography and nanoimprinting), irradiation of metallic nanoparticles (MNPs) embedded in a dielectric medium with energetic ions has demonstrated the possibility to transform near-spherical particles into well-aligned, high aspect-ratio nano-rods, a process known as “ion-shaping”. The ion-induced shape transformation process of MNPs has been studied predominantly with amorphous silicon dioxide as the host matrix for various metallic nanoparticle species. It has recently been suggested that the elongation process of Au NPs is linked to the ion track formation process in silicon dioxide and is governed by Au diffusion into the under-dense track core region [1]. If this is true, the relationship between the nanoparticle and the ion track core region dimensions should be more relevant than the relationship with the total ion track radius, as previously proposed [2].

In the present work, we present the shape transformation of nearly spherical Au nanoparticles upon irradiation with 185 MeV Au ions at different fluences in two configurations: (i) embedded in, (ii) and at the interface of amorphous silicon nitride and silicon dioxide. We have previously characterised the morphology of ion tracks formed in both amorphous silicon nitride and silicon dioxide which show a similar morphology, yet differences in the formation process were observed. Ion shaping experiments carried out using the two materials will help to test and expand the currently proposed models that are still controversial. Depending on the host material configuration we observed either transformation into facetted nanoparticles when embedded in amorphous silicon nitride, high aspect-ratio nano-rods when embedded in silicon dioxide, and long nano-rods with preferential elongation into the amorphous silicon dioxide layer when located at the interface. Complementary numerical calculations based on the three-dimensional version of the inelastic thermal spike model were carried out to simulate the thermal environment for the three configurations. The combination of experimental and numerical results suggests that the ion-shaping process is strongly influenced by the thermo-physical properties of the three materials.

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The Role of the Human Papillomavirus in Head and Neck Cancers: Cancer Stem Cell Diversity and Response to Radiation.

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Introduction

Cancer stem cells (CSCs) play a fundamental role in tumour progression, metastases and recurrence. These are the most treatment resistant of tumour cells, accelerating their replication and tumour repopulation in response to tumour depletion[1]. The human papillomavirus (HPV) has emerged as a discrete aetiology in head and neck cancers (HNC). They demonstrate consistently better responses to radiotherapy initiating several clinical trials to de-escalate treatment[2]. This study investigates the *in vitro* differences in CSC responses in head and neck cancers to radiation in terms of their HPV aetiology.

Method

Six HNC cell lines were investigated. UM-SCC-47, UPCI-SCC-090 and UPCI-SCC-154 are HPV+ and UM-SCC-1, UM-SCC-17a and UM-SCC-22a are HPV-. Cells were irradiated in T25 flasks with 4 Gy using a Varian 6 MV linac and a RS2000 irradiator at 160 kVp and 25 mA. Flasks were filled with medium, encased in a paraffin wax block and mounted on 7 cm of RW3 to provide full scatter conditions. Sham-irradiated flasks were used as controls. CSC proportions of cell populations were measured at 24, 48 and 72 hours, and again at 10 days post irradiation. CSCs were identified by putative cellular markers CD44 and aldehyde dehydrogenase (ALDH), using flow cytometry.

Results

Triplicate analysis of non-irradiated UM-SCC-47 cell cultures showed a mean CD44+/ALDH+ population to be 2.87%$\pm$0.219, 5-fold that of the UM-SCC-1 population which was 0.57%$\pm$0.077. UM-SCC-47 and UM-SCC-1 showed increased ALDH+/CD44+ proportions of population following 4 Gy irradiation. The proportional increase for UM-SCC-47 was 3 to 4 times the control within 72 hrs post irradiation. After 10 days these cultures no longer presented significant differences in CSC population against the control. UM-SCC-1 showed the most significant CSC increase 24 hrs post irradiation and a persisting elevation in CSCs 10 days after irradiation.

Conclusion

CSCs display significant heterogeneity between cell lines warranting investigation of the effect aetiology has on intrinsic population numbers and treatment responsiveness.

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Filling the gaps in radiological dose assessment from natural radioactivity: Development of ^{231}Pa AMS measurements with the 14UD at ANU

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There is a wealth of published data on the movement and partitioning of the uranium-238 decay series radionuclides within the natural environment that can be used for radiological dose assessment. However, limited information exists for the uranium-235 decay series (also known as the actinium series). Only three isotopes in the actinium series, ^{235}U, ^{231}Pa and ^{227}Ac, have half-lives greater than a month. Biological accumulation of these isotopes can lead to a radiological dose to the environment or to humans, through ingestion of food and water or via inhalation of particulates. The degree to which these isotopes are biologically accumulated is therefore potentially controlled by the chemical properties of these elements. The extent of other radiologically-significant isotopes lower in the series present in biological systems is therefore controlled both by the chemical properties of these three isotopes in the environment, and their biological uptake.

While the activity concentrations of ^{235}U, at the head of the actinium series, are ~20 times smaller than those for ^{238}U, the effective dose per unit of activity for the actinium series isotopes can be 10 to 20 times higher than those for the ^{238}U series elements. Furthermore, there are no suitable chemical or isotopic analogues for modelling the significance of ^{231}Pa (and ^{227}Ac) movement and accumulation in environmental media, and hence there is a need for direct measurements.

We report on the development of AMS ^{231}Pa measurements on biological materials using the 14UD accelerator at the ANU, and on a new, safer radiochemical extraction method for the yield tracer ^{233}Pa. Ultimately this will allow more accurate prediction of the significance of the radiation doses received from actinium series radionuclides to the environment and/or humans through the ingestion or inhalation pathways.

Probing Location of Rare-Earth Ions in Zinc Oxide Matrix by RBS Channeling for Spintronic Applications

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Zinc oxide (ZnO) is a promising dilute magnetic semiconductor (DMS) host material with the potential to show room temperature ferromagnetism (RTFM) under suitable doping conditions [1]. Transition-metal doped ZnO remains the most widely studied ZnO-based DMS, although conflicting magnetic order has been reported in similar systems. Rare-earth (RE) elements were shown to induce large magnetic moments in semiconductors such as GaN, and in principle can also be incorporated into ZnO to form DMS [2-5]. A systematic investigation is required for better insight into location and magnetic interactions in RE doped ZnO (ZnO:RE), as the observed magnetic coupling is often associated with the defects [4].

We report results obtained from 30-40 keV RE (Gd, Er and Tb) ions implanted into ZnO single crystals with fluences ranging from 6.6×10^{14} to 3.0×10^{16} cm^{-2} resulting in 0.7 to 12% RE atoms at an average depth of ~12 nm. Rutherford backscattering spectrometry in channeling condition (RBS/C) were carried out to study the location of RE in ZnO matrix using 2 MeV Helium beam obtained from 3 MV Van De Graff Accelerator. RBS/C revealed that for 9.0×10^{14} cm^{-2} ZnO:RE around 100% of the Gd/Er atoms occupied Zn substitutional lattice sites [2,5]. Annealing at 650 ˚C had profound effects on the Gd/Er atomic positions and only around 78 to 81% were found at substitutional sites and the rest driven out to random interstitials. Energy-filtered TEM revealed that interstitial RE atoms may form RE-rich nanocrystals. Temperature dependent resistivity results showed characteristics of degenerate semiconductors, with an anomalous feature at low temperatures [3]. ZnO:Gd samples exhibited negative magnetoresistance (MR) with lower MR values in annealed samples, suggesting reduced free scattering centres due to enhanced magnetic ordering. RTFM was observed in annealed ZnO:RE with a hint of mixed magnetic phases as seen in the M(T) data. Possible mechanisms for magnetic order, supported by structural, magnetotransport, and magnetization measurements, will be presented in the conference.

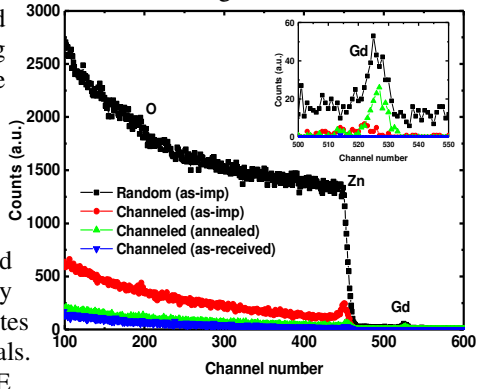

Fig. 1: Random and [0001]-aligned RBS spectra of 9.0×10^{14} Gd cm^{-2} implanted and annealed ZnO [2]. Inset: magnified Gd peaks.

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Recent AMS ^{14}C Applications in Environmental and Climate Research

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After a short discussion on recent technical developments in accelerator mass spectrometry (AMS) radiocarbon (or ^{14}C) analysis at ANSTO, this paper focuses on the applications of radiocarbon in environmental and climate studies through the illustration of several applications in the field, which have been carried out at ANSTO.

With the recent installation of two new machines from NEC, the Centre for Accelerator Science at ANSTO now has four tandem accelerators (10 MV ANTARES, 2 MV STAR, 1 MV VEGA and 6 MV SIRIUS), which are capable of measuring a range of long-lived radioisotopes including ^{14}C, ^{10}Be, ^{26}Al, ^{129}I, ^{36}Cl, ^{236}U and ^{239}Pu by AMS for various applications in earth, environmental and climate research. Three of the four accelerators are currently used for ^{14}C analysis. In addition, there have been improvements in AMS ^{14}C target preparation, especially for microgram-sized samples. Samples containing as little as 10-20 µg of carbon can now be reliably prepared and analysed at ANSTO [1-2]. This has opened up opportunities for radiocarbon analysis of new materials such as single grains of specific skeletal components of carbonate sediments (eg, single foraminifera) and gas species (CO, CH_4) trapped in ice cores.

Radiocarbon is one of the most common and important cosmogenic radionuclides for building reliable chronologies for various materials and archives for the study of environmental and climatic changes for the Holocene and late Pleistocene. Radiocarbon is also employed as a powerful tracer of the carbon cycle, climatic systems and environmental processes. In this paper, several case studies will be discussed to show the breath of radiocarbon applications in these scientific areas. They include dating of recent Antarctic mosses for the study of biological effects of climate change [3], study of soil carbon dynamics using radiocarbon in deep soil carbon [4], investigation of CH_4 sources during the Last Glacial Termination through $^{14}CH_4$ measurements in ancient polar ice [5], and investigation of spatial and temporal variations in surface ocean ^{14}C using paired measurements of U/Th and ^{14}C on corals for better understanding of past climate variability and ocean circulation changes [6].

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How exploding stars have helped identify erosion hot-spots in catchments adjacent to the Great Barrier Reef

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There is considerable evidence that the amount of sediment reaching the Great Barrier Reef (GBR), Australia, has increased since agricultural development commenced in the 1870's. This sediment is having deleterious effects on freshwater and marine ecosystems. However, identifying the primary source and processes driving the increased sediment delivery has been challenging due to the large size and diversity of adjacent catchments.

This study was the first of its kind in Australia to compare long-term (~100 to >10,000 year) erosion rates derived from terrestrial cosmogenic nuclides (TCN's; ^{10}Be) with contemporary erosion rates obtained by monitoring sediment fluxes over ~5-10 years. This study was conducted in the Burdekin catchment, which is the largest source of contemporary sediment to the Great Barrier Reef lagoon. Following rigorous testing of the assumptions for this technique [1], the ratio of these two data sets provided a measure of the accelerated erosion factor (AEF) for the major sub-basins in the Burdekin catchment [2].

Results show that three out of five of the major sub-catchments in the Burdekin basin have AEF's greater than 1.0. In the Bowen and Upper Burdekin sub-catchments, the AEF is 7.47 (± 3.71) and 3.64 (± 0.5), respectively. This suggests that erosion rates in these sub-basins are well above the natural background erosion rates, which is largely to be due to the relatively high slopes, higher rainfall and intensive land use (grazing and mining) compared to other parts of the catchment.

This study has important implications for how GBR water quality targets are set and evaluated. Without an understanding of the natural susceptibility of a catchment to erosion, resources for remediation may be incorrectly allocated to areas that appear to be producing high sediment yields, when in fact they have landscape attributes that generate large volumes of sediment even in the absence of land use change (e.g. agriculture). Remediating catchments with high AEF's to reduce erosion and sediment delivery is likely to take several decades, and will require a range of approaches including pasture and rangeland management, as well as targeted erosion control in highly gullied landscapes.

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The Room-Temperature Synthesis of HfO_2/HfO_x Heterostructures by Ion-Implantation

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Implantation of Hf films at room temperature with 3 keV oxygen ions is shown to produce HfO_2/HfO_x heterostructures suitable for resistive switching applications [1]. The resulting films are characterised by transmission electron microscopy (TEM), glancing incidence x-ray diffraction (GIXRD), electron Rutherford backscattering spectrometry (e-RBS), reflection electron energy loss spectroscopy (REELS) and x-ray photoelectron spectroscopy (XPS).

Resistive switching characteristics of the films are compared with those of films grown by ALD at 200ºC. Analysis shows that irradiation to a fluence of $1x10^{17}$ $O.cm^{-2}$ is sufficient to produce a polycrystalline (monoclinic HfO_2) HfO_2 layer extending from the surface to a depth of ~12 nm, and an underlying graded HfO_x layer extending an additional ~7 nm. The bandgap, dielectric strength and resistive switching characteristics of the films are shown to be indistinguishable from those of amorphous films deposited by atomic layer deposition (ALD) at 200 ºC. These results demonstrate the efficacy of ion-implantation for low-temperature synthesis of functional oxide layers.

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Latest Geant4 developments for PIXE applications

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In Geant4, atomic relaxation simulation is articulated through two stages: 1) The creation of a vacancy by a primary process e.g. photoelectric effect, Compton scattering and ionisation. For the ionisation process an additional particle induced X-ray emission (PIXE) cross section is used. 2) The relaxation cascade is triggered, starting from the vacancy created by the primary process. Fluorescence X-ray or Auger electrons and Coster Kronig transitions are generated through radiative and non-radiative transitions, based on the respective transition probabilities and tracked in the simulation. The goal of this project is to improve the set of Geant4 shell cross sections for PIXE, based on the state of the art recommendations documented in [1]. In particular the cross section of protons and alpha particles we propose to include in Geant4 are based on [2], [3] for K, L and M shells. The novel shell cross sections, called ANSTO ECPSSR, will have important implications in nano-medicine where high atomic number nanoparticles (NPs) internalized in cancerous cells can be used to boost energy deposition. McMahon et al. demonstrated that Auger electrons play a crucial role in the deposition of energy close to the NP [4]. The accuracy of the Auger electron and Coster-Kronig transition is strongly connected to the precision of the X-ray fluorescence modelling as its yield is 1 minus the fluorescence yield ω. Besides X-rays deriving from K, L and M shells can deposit energy in the cell as well, therefore an accurate prediction of Auger electrons and Coster-Kronig transitions and fluorescence X-rays, together with specialized models adapted to nano-scales (such as Geant4-DNA models) are crucial to characterise this novel radiotherapy technique.

ANSTO ECPSSR cross sections for proton and alpha particles have been integrated in Geant4 for PIXE simulation. This study shows that all the already-available Geant4 alternative PIXE cross sections provide similar results for K and L shells (and sub-shells). The ECPSSR "Form Factor" and ANSTO ECPSSR approaches both handle M sub-shell de-excitations. The two alternative sets, while providing more similar results for K and L shells, show significant differences when modelling the M shell. The novel ANSTO ECPSSR cross sections will be released publicly within Geant4 in the next future. The next step of the project is to compare systematically the alternative approaches to shell ionisation cross sections to be used in Geant4 for PIXE applications with respect to the energy of the incident particle and of the target material. We will also validate the application of Geant4 for PIXE simulation capabilities and atomic relaxation against original experimental measurements performed at ANSTO.

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Geant4 and ANU Auger-electron cascade Monte Carlo model comparison

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The extreme radiotoxicity of Auger electrons and their exquisite capacity to irradiate specific molecular sites has prompted scientists to extensively investigate their radiobiological effects [1]. In radiotherapy Auger-electron emitting radionuclides are of great interest because of their short range, which is a very important feature to protect normal tissue adjacent to the targeted tumour [2]. This unique feature offers some distinct advantages compared to the more commonly used long-range beta electrons, such as a reduced cross-fire irradiation of non-target healthy cells and a higher ionisation density within the immediate vicinity of the decay site, which is generally associated with high(er) biological effectiveness [2][3][4][5][6][7]. Auger-emitting radionuclides have shown very promising effects in vitro and in vivo in animal studies over the last decade [8][9]. Emission spectra of Auger-electron emitting radionuclides are essential for dosimetric calculations to quantify the biological damage delivered to the target [6]. In the past three decades several authors published calculated emission spectra of selected radionuclides using either deterministic or Monte Carlo computational methods [10][6][11].

Geant4.10.04 extended example (radioactive decay 01) have been used in this study [12][13][14]. We compared results obtained with Geant4 and the ANU model to other data sets for I-123, I-124 and I-125 [2]. Yield ratios of Geant4 and other data sets to ANU are plotted. Performance of Geant4 and a recently developed Monte Carlo model of Auger cascades have been compared. Good agreement with the published data is found [15].

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Design of a Dedicated Beamline for Ocular Oncology at the Australian Bragg Centre for Proton Therapy and Research

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Plaque brachytherapy is used to deliver ionsing radiation to some melanomas of the eye to achieve local tumour control and preserve the eye-globe. Some tumours of the eye are unsuitable for plaque brachytherapy and enucleation is often the only choice for satisfactory local control. The availability of proton beam therapy (PBT) widens the possibilities for globe and sight-saving treatment in these patients, whilst reducing radiation dose to normal structures such as the brain, optic nerves and pituitary gland [1, 2]. Conventional treatment of the eye with PBT requires the insertion of tantalum clips to locate the tumour in the treatment beam. The Australian Bragg Centre for Proton Therapy and Research is currently being built in Adelaide, South Australia, which provides the opportunity for a beamline to be designed and dedicated to treatment of eye cancers. The design of an ocular oncology beamline will be presented including a discussion of the components that are planned to be used in its assembly. Additionally, the patient imaging and beam targeting systems will be discussed including the embedding of real-time monitoring of tumour target position [3]. This innovation should avoid the use of tantalum clips to locate the tumour in the treatment beam eliminating the need for surgery. Shielding considerations for the beamline are avoided by using a high energy proton therapy bunker where the shielding for that bunker is more than sufficient for the ocular beamline.

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Accelerator mass spectrometry of ^{93}Zr at ANU and its applications

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The long-lived radionuclide ^{93}Zr ($t_{1/2} = (1.61 \pm 0.05)$ Ma)[1] plays an important role in nuclear astrophysics as well as in nuclear technology and nuclear waste management. Stellar production of ^{93}Zr happens mainly via the slow neutron capture process. Neutron capture cross sections in the keV range are one of the main parameters to model this process. They are particularly interesting in the Zr mass range, as this is the matching point between two components of the slow neutron capture process occurring in two different stellar environments. In nuclear reactors large amounts of ^{93}Zr are produced, predominantly by fission, but also by neutron capture on stable ^{92}Zr, as zirconium alloys are used for cladding of nuclear fuel rods. Due to its longevity ^{93}Zr is important to consider for nuclear waste management. Spontaneous fission of uranium and thorium along with neutron capture leads to natural terrestrial production of ^{93}Zr and consequently its presence in the environment.

Despite its importance the neutron capture cross sections for ^{93}Zr are poorly known for stellar (keV) as well as thermal (meV) energies. Owing to its long half-life and its low-intensity and low-energy gamma transition, determination of ^{93}Zr by decay counting is extremely difficult. Accelerator mass spectrometry (AMS) is an ultra-sensitive technique for the determination of isotopic ratios, typically of radionuclides to their stable isotopes, and offers an alternative approach. The main challenge here is background induced by stable isobars (e.g. ^{93}Nb for ^{93}Zr). At ANU, AMS for the challenging isotope ^{93}Zr has been recently developed [2] and the technique was applied for the determination of the neutron capture cross sections of ^{92}Zr for thermal and stellar energies. In the future the achieved unprecedented low limit of detection for ^{93}Zr/^{92}Zr $\sim 10^{-12}$ at ANU might even allow the determination of ^{93}Zr in natural samples and the usage of the isotope as a tracer for environmental processes.

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Geant4 for proton and heavy ion therapy

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Monte Carlo codes are widely used in proton and carbon ion therapy as tools to verify clinical treatment planning systems, to develop associated quality assurance detectors and also to improve the delivery of the treatment to the patient. We will illustrate the physics capability of Geant4 to perform dosimetry, micro- and nano-dosimetry in the context of proton and heavy for carbon ion therapy, together with its validation against experimental measurements. We will illustrate a variety of potential uses of Geant4 of interest for the proton therapy facility under construction in Adelaide.

Pre to post-bomb ^{14}C history in the western Philippine sea: insights into the oceanographic changes in the South China Sea

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Compared to the natural production of ^{14}C, thermonuclear tests have produced a globally abnormal ^{14}C signal. To examine and reconstruct ocean circulation in the South China Sea, we generated a pre to post bomb ^{14}C time series from a *Porites lobata* coral in the western Philippine Sea. Results show an early bomb peak in late 1955 as seen in corals from Ishigaki, Guam and Makassar Straits which is due to the immediate advection of ^{14}C labelled water from nuclear test sites. Our post-bomb $\Delta^{14}C$ peaked at 154 ‰ in 1975, which is ~10 years lagged behind the atmospheric peak, consistent with other marine records. Our coral also displayed clear seasonal $\Delta^{14}C$ variability indicating different surface waters passed our coral site in western Philippine sea due to the seasonal variations of the East Asian Monsoon.

Past geomagnetic field reconstructions using cosmogenic radio nuclides in the Antarctic ice core

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Geomagnetic excursions provide information on field mechanics and serve as a chronostratigraphic tool. Interpretation of sedimentological paleointensity records is complicated, and volcanic rocks provide only non-continuous records. Another means for reconstructing paleomagnetic intensity is analyzing cosmogenic radio nuclides. In this study, we reconstruct the Blake and the Post-Blake as well as Laschamp Excursions using the cosmogenic radio nuclide ^{10}Be in the Dome Fuji ice core. It has been reported that the Blake Excursion and the Post-Blake Excursion occurred within the Brunhes Chron, at around 115 ka and 100 ka, respectively. These two excursions occurred in quick succession. The Post-Blake Excursion is relatively poorly studied, only being reconstructed from sediments and volcanic rocks. Results indicate there is a significant peaks in ^{10}Be flux that is thought to be reflect respectively the Blake and the Post-Blake Excursions. The maximum ^{10}Be flux during the Post-Blake Excurison is similar to that of the Blake Excursion, suggesting that the geomagnetic dipole field during the Post-Blake Excursion weakened by the same amount as during the Blake Excursion. We also compare the results for the Laschamp Excursion that we also reconstructed from the same ice core to discuss the nature of individual excursions inferred from the cosmogenic radio nuclides data.

The new SIRIUS accelerator system at ANSTO: Design, capabilities and recent applications for environment, radiation health physics, material modification and characterisation using accelerated heavy ions

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The Centre for Accelerator Science (CAS) facility at ANSTO has recently been expanded with the new 6 MV SIRIUS accelerator system with multiple beamlines for Ion Beam Analysis and Accelerator Mass Spectrometry [1].

The beamlines, end-stations and data acquisition software for the accelerator mass spectrometry (AMS) were custom built by NEC for rare isotope mass spectrometry, while the beamlines with end-stations for the ion beam analysis (IBA) are largely custom designed at ANSTO using in-house expertise. An overview of the 6 MV system and its performance will be given with recent outputs in research fields of radiation health physics, materials modification and characterisation, environment and paleo-climate change.

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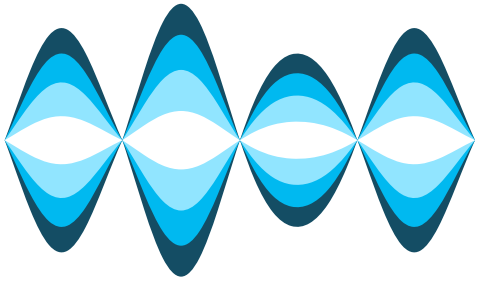

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