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"... for the encouragement of studies and investigations in Science Art Literature and Philosophy ..."

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Editorial

This special issue of the *Journal and Proceedings* provides a tribute to the memory of Jak Kelly, a past President of our Society. Jak was an experimental physicist who spent the greater part of his career at the University of New South Wales, including serving as the Head of School for Physics. We hear in this issue from colleagues and former students about the influential role Jak played in mentoring their own careers, of work that Jak led them into, of the essential elements of physics that he instilled in them at formative stages in their lives – the arts and skills of problem solving, of looking at the big picture and thinking beyond the constraints – all hallmarks of good science and good scientists.

Richard Newbury, the current Head of Physics at UNSW, begins, comparing the School today to how it was in Jak's time, and musing at how the world of academia had changed, not necessarily for the better. David Mills describes how Jak led him into the world of solar collectors – an unfashionable field at the time – and to the development a new type of surface for the efficient collection of radiation, one which later became the key technology behind millions of solar hot water systems in China. We have three articles from former PhD students of Jak. Patrick Krejcik learnt the tools of the trade of particle accelerators under Jak in the High Voltage Accelerator Laboratory at UNSW. He ended up working with Stanford's Linear Accelerator, where many fundamental discoveries underlying our current understanding of particle physics have been made. Patrick writes on the history of particle accelerators at Stanford. Zoltan Kerestes is now a medical physicist at Sydney's Royal North Shore Hospital, practising a different kind of physics to that he learnt under Jak. But the lessons Jak instilled in him have played an essential part in developing his career. Zoltan espouses some of these lessons for us, along the way giving us insights into Jak's irrepressible character and his sense of humour. Jim Williams was enticed by Jak into a PhD using the soon-to-be installed Cockcroft-Walton accelerator at UNSW. That experiment didn't quite go the way it was planned, or at least to schedule – not an unusual story with frontline science, but one that provided an invaluable lesson into how science actually works and led Jim into the new field of ion channelling. He recounts some of the experiences, and the influence of Jak, which has underpinned his own successful career that has ended up at the Australian National University. Heinrich Hora was a fellow academic at UNSW with Jak, heading theoretical physics while Jak was the driving force behind experimental physics. Heinrich describes some of the research avenues that his interactions with Jak led him into. The final contribution for this special edition comes from Andrew Ong, also at UNSW, but having just completed his PhD – he was the Society's Jak Kelly Award winner in 2012. We begin the edition by reprinting Jak's Obituary, as published in *Vol 145* of this Journal.

Michael Burton
Hon. Secretary (Editorial)

This special issue of the Journal has been supported by both the School of Physics and the Faculty of Science at the University of New South Wales.

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Obituary

Professor Jak (John Charles) Kelly FRSN

(14 February 1928 – 11 February 2012)

Re-printed from Vol 145, Part 1, Nos. 443 & 444, pp 101-102.

Jak was born John Charles Kelly in 1928, in Borenor, about 30 km west of Orange in New South Wales. The son of a contract wheat harvester, he obtained a scholarship to the De La Salle Bros. school in Armidale and progressed to the University of Sydney, where he fell in love with physics and caving. Jak was founding President of Sydney University Speleological Society in 1948 and became a local caving icon. Opening the 50th SUSS meeting in 1998, he recalled running out of oxygen: "People were unable to strike matches for their cigarettes. It took 45 minutes to get down and 5 minutes to get out!"

Graduating in 1950, Jak worked at the National Standards Laboratory in Sydney, publishing his first paper in Nature in 1950 on his invention of vibration measurement using multiple beam interferometry. In 1953, he married Irene Traub, who remained at his side for the next 59 years and is known to many in the Society.

In 1955 Jak moved to the University of Reading to complete a thin film PhD project under O.S. Heavens. In order to create better quality thin films, he invented Electron Bombardment Deposition using a pendant droplet of melted metal heated by an electron beam. It became a standard method of high temperature metal evaporation. Graduating in 1958, he worked at Harwell on radiation damage in crystals, grown using his single drop method.

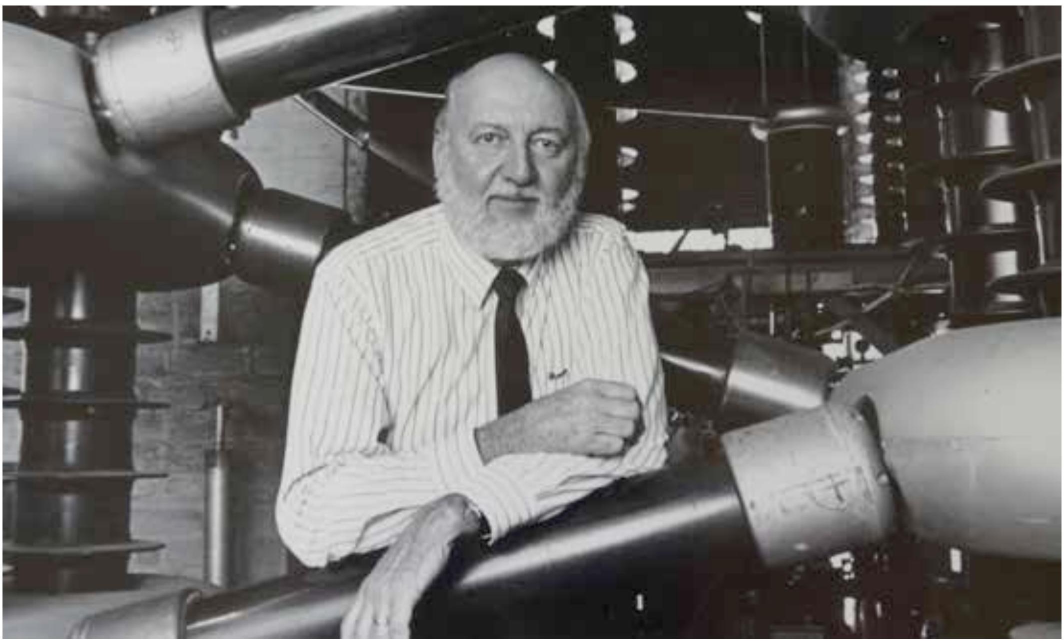
Jak returned to Australia in 1961 to the UNSW School of Physics, where he remained for the rest of his salaried career, writing more than 150 papers. He specialised in ion beam deposition, patenting several improvements, and co-authored three books. He served as Chair of the Australian Institute of Physics in 1965-66, became a Fellow of the Australian and UK Institutes of Physics, and in 1975 was created a Doctor of Science for his body of work. His curiosity was broad and his subsequent cooperation with other groups included thermoluminescent dating, using ion implantation to improve the attachment of bone cells to prosthetic surfaces, the modelling and deposition of thin film solar energy absorbers, irradiation of wool using ion beams to improve wool properties, studying low energy nuclear reactions, and proposing laser fusion improvements.

At UNSW Jak served as Head of School and Science Faculty Chairman (1985-89), and Chairman of the Australian Academy of Science Section A and other committees. He retired in 1989, remaining a visiting professor, and became Editor of Australian Physics (1992-98), Honorary Professor of Physics at Sydney University in 2004, and subsequently President of the NSW Royal Society (2005 and 2006). He was appointed an Inaugural Fellow of the Society in 2009.

Jak was an outstanding ambassador for Physics. His flamboyance, fluency, and sense of humour found a ready audience in younger students and drew many into Physics as a career. Many still remember him playing the scientific sage in 1980 in a Robin Williams ABC Science Show spoof about the discovery of a 60,000 year old fossilised beer can. He also supervised many PhD students who became friends and remained so.

Jak died with his family around him, 3 days before his 84th birthday. He is survived by Irene, who for years assisted the Sydney RSNSW office; their daughter and former science broadcaster Karina Kelly, who preceded Jak as President of the Society; and sons Michael and Julian.

David Mills
John Hardie
Heinrich Hora



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Jak Kelly – Peerless Head of the School of Physics, UNSW 1985-1989

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Abstract

Jak Kelly served as the Head of the School of Physics at the University of New South Wales from 1985 to 1989. This article provides a perspective of life in the School of Physics in Jak's day compared to 2013, as seen and experienced by the current Head of School.

I have been asked to write something about Jak Kelly. My instructions are to write something about Jak Kelly the man and the scientist and something also from a Head of School perspective, the suggestion being to contrast the job as it was in Jak's time as Head (1986-1988) with the nature of the job today. Actually this is a little difficult because I came to Australia only in 1991 (Jak had by then already retired), I didn't know Jak and, although I did see him in the corridors of the School from time to time, we never spoke. However a little informed guesswork is possible and a sketch of things as they were then can be gleaned from the recollections of staff who have been with us in the School since the 80s. One thing I am sure about is that the job, in some respects, is very different today.

I attended Jak's funeral in 2012 and met many of his family and friends. It was obvious as we heard from the many in attendance that Jak was a very special man, a talented researcher and teacher and a man with wonderful family and many devoted friends, colleagues and students he'd taught and supervised.

So let's look back a bit to the earlier days of the School, 20-25 years back.

When I arrived at the School in February 1991, Bob Starrett, a Professional Officer in the School since time immemorial, took me to a (very) dusty room half way along the Lower Ground Floor of the Old Main Building and said "I want to show you something, I think you'll find it interesting". Half an hour later with Bob still fiddling with diecast boxes and BNC cables I was becoming quite impatient when a rotating globe icon appeared in the corner of the 10 inch black & white monitor and Bob said: "that's the internet, it's great isn't it!" Fascinating, Bob. What does it do?" After a 10-minute briefing from Bob I remained unconvinced, couldn't see any potential in the daft distraction Bob called the Internet, and we went off to lunch.

It's quite likely that Jak wouldn't have been able to anticipate either – who could have guessed? – the impact the internet would have on so many things, changing the nature of work, leisure and things one could put in the category "irritations".

I say irritations because, once upon a time, to request that someone at the other end of campus, or further afield, do something required a phone call or often a letter. In

Jak's time a letter would be drafted, typed, proofed, put into an envelope and posted. The recipient would receive the instruction up to a week later. The advantage of the inertia build into this system of communication, aside from the extra work required is that people issued less requests for action or for compendious data sets etc. An even bigger advantage was that people probably thought more carefully about the reason for their requests for action and information. Perhaps with the time saved people were able to engage in more profound activities and not the "thought bytes" that we must sometimes be content with nowadays?

So what was Jak doing back then, BTI (Before The Internet)? One of Jak's earliest papers was a nice piece of work published in *Nature* in March 1950 and concerned the use of interferometry for sensitive measurements of vibration – for example vibration of buildings. This work was performed at the National Standards Laboratory, CSIRO. By the mid-50s Jak was at the University of Reading studying for his PhD and had moved on to thin film physics, radiation detectors and the properties of molten metals, work which Jak continued until the early 1960s, firstly at Reading, then the Atomic Energy Research Establishment, Harwell and then at the School of Physics, UNSW, having taken up a permanent academic position in the School in 1961.

I am fortunate to have to hand a copy of Jak's D.Sc. thesis from 1972, a collection of some 39 papers that form a very nice "roadmap" for Jak's research directions.

A key development in Jak's "Materials Irradiation Laboratory" in the School of Physics was the availability of a 1.2 Megavolt accelerator, a machine "inherited" from ANU and installed on UNSW's Randwick Campus. This machine became the workhorse for much of Jak's subsequent research. Jak worked on sputtering, particularly of the Alkali Halides, and on the interaction of energetic electrons with crystal lattices, particularly channelling in crystals.

Figure 1. A thoughtful looking Jak in front of the high voltage stacks of the 1.2 megavolt accelerator at Randwick campus. Photo courtesy of Patrick McMillan.

At this time Jak also co-authored a series of very nice theory papers. The series on "Wave Theory of Lattice-Directed Trajectories", written with Hans Nip, which appeared in Physical Review B are a good example of this work.

Figure 2. Jak with his research group from circa 1989. From left to right: David Cohen (ANSTO) PhD student, QiChu Zhang (UNSW) PhD student, Zoltan Kerestes (UNSW PhD student, Bruce Beilby (UNSW) PhD student, Jak Kelly, Eric Clayton ((ANSTO) PhD student, Mathew Borland (UNSW) PhD student, Bob Dalglish (UNSW) PhD student, Jules Yang (UNSW) Jak's Technical Officer, Rolf Howlett, Jak's ARC Co-investigator. Many thanks to Patrick McMillan for identifying these people and to Ranji Balalla for supplying the picture from her personal album.

Figure 3. Illustrious company! Jak shakes hands with soon-to-be Head of School of Physics John Storey. Seated, left, Dean of Science at UNSW Ted (Viliam Teodor) Buchwald, Professor of Applied Mathematics and Dean of Science 1980-88, and right, the late Gavin Brown who was Dean of Science at UNSW 1989-1992 and then Vice Chancellor of the University of Adelaide and of the University of Sydney.

The work at the Materials Irradiation Laboratory led to international recognition for Jak for his lab and work on ion implantation and defects in materials.

Jak became Head of the School of Physics in 1985 and served a 3-year term. During this period he was also elected Chair of the Faculty of Science. Jak took over the headship from Ken Taylor and was succeeded in 1988 by John Storey.

In 1985 some aspects of School life were quite different. The academic and general staff complements were larger. All senior members of academic staff had a personal secretary – unthinkable today as this would be prohibitively expensive – but essential because everything formal would be typed, usually on an IBM "Golfball" typewriter. Typing anything with a significant amount of mathematical content would be excruciating because the golfballs would need to be continuously switched in and out to provide the range of symbols and fonts required.

Nowadays academics type practically everything themselves but in the 1980s a professor would work closely with her or his secretary and a mistake on an ARC application requiring re-typing would surely have put some serious strain on this working relationship and presumably needed the odd lunch to restore equilibrium.

There is a handy segue here. I have talked to half a dozen people in the School who knew Jak and there is a constant theme in their remarks: Jak was a kind and most generous Head of School, he was always extremely supportive of junior staff.

Figure 4. Jak Kelly with his Head of School PA (1986-88) Ranji Balalla at Jak's retirement party. Ranji is an excellent source of anecdote from that time (and is still in the School). One winter day Ranji told Jak that she'd never seen snow. The next morning Jak put some keys on Ranji's desk and said: you and your family should go down to stay at my cabin in Lake Eucumbene, you'll see some snow there! Typical Jak Kelly thoughtfulness and generosity.

Furthermore, Jak was a terrific lecturer, universally appreciated and much liked by students. He had a wonderful sense of humour, often more than a little mischievous. One colleague commented that Jak would enjoy "stirring the pot", this done, of course, without mal-intent.

Talking to two senior colleagues who knew Jak well and were in the School when he was Head has provided an interesting perspective – no names here for obvious reasons!

There was, apparently, regular and "robust" discussion about who should have which space in the School and how much of it. So no change there, space has always been one of the most challenging of all issues and a perennial headache for heads.

I am sure Jak managed space issues with aplomb and probably used humour, quite liberally, to defuse potentially explosive situations. I say potentially explosive situations because it would seem there have always been one or two people in the School who are burdened with an unrealistic view of their own co-ordinates and are surprised to be told that they are not, in fact, at the centre of the Universe. With what I've discovered about Jak I think he would also have dealt with these characters with composure and style.

Today I asked a former Head of School for his view of how the job has changed over the past ~30 years, particularly with regard to changes in the nature of the job and changes in workload due to the information technology and communications revolution that's taken place in the intervening years. I was stunned to be told that a Head of School in the 1980s and early 1990s could contain a full year's School correspondence in a single manila folder containing a stack of sheets approximately one centimetre thick! That sounds like a party trick; today the correspondence accumulated in a few days would exceed that, if printed out.

Many other things have changed, too. OHS was no more than an acronym in the 1980s. Now it is a vast, consuming activity with truly byzantine intricacies. Key performance targets (KPTs aka KPIs) were unknown. Human Resources was "Personnel" and a staff appointment could be made by mailing a single sheet of paper.

But let's be clear about one thing here, Physics at UNSW has always been strong, the School having both strength and depth, and in Jak's time the quality of teaching and research was just as good, if not superior to, what it is today.

So what does this all add up to? For you, dear reader, who has passed the point in life at which one starts to acquire wisdom more rapidly, you will say: I know this already, many things in the life of the School have changed, some for the better, and some not.

So it's one step forward and two back? Possibly. It is tempting to wonder whether or not we are achieving more these days. Not greater numbers of this and that as measured by bare metrics but profound discoveries, things that are of genuine benefit humanity, things that will help us solve some of the challenges facing the planet and persuade naysayers that now is the time for action.

So what would Jak do? Well I think he'd manage things the way he did back then, with clear and thoughtful leadership and with kindness, generosity and a good dose of humour about it all – and I think he would manage rather well.

Richard Newbury

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Richard Newbury has been at the School of Physics, UNSW since 1991. He is a condensed matter experimentalist and has a keen interest in learning and teaching. He was Director of First Year Studies in Physics 1999-2005 and has been Head of the School of Physics from 2006.

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A Timely Intervention – Jak Kelly and Solar

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Abstract
This is a personal recollection of my cooperation with Prof. Jak Kelly, who was a friend before he became my father-in-law. Only once did we cooperate scientifically, with an outcome that that we could not have predicted.

Introduction

Jak Kelly and I met in 1977 in the UNSW School of Physics. I was born in Canada, and immigrated into Western Australia after travelling for two years in Africa and Asia. As a graduate student in Physics at WAIT, now Curtin University, I had soon developed an unrefined concentrator concept called the prism concentrator for PV cells (developed three decades later into a ten million dollar start-up in California by people who discovered my work, but that is another story). In 1976, my supervisor suddenly pulled up stakes and departed for Fiji, leaving me without a supervisor experienced in solar energy. After writing to all of the Universities in Australia with solar programs, I joined the UNSW School of Physics as a Master's student under John Guitronich, who had done pioneering experiments with a solar furnace in the 1960s and was trying to set an optical concentration record for parabolic trough concentrators. John kindly agreed to supervise me as a Master's programme even though my area of interest, called "non-imaging optics", was distant from his own.

I began to publish papers in my own little field, with John as co-author, and I soon upgraded to a PhD programme. We received some federal energy research money and populated the solar lab with some bright young researchers. Our lab was opposite the hall from Jak Kelly's office and I found Jak very welcoming and interesting, so I occasionally popped in to chat about the world at large and the microcosm of departmental politics. We had little in common in research terms – he was a materials experimentalist with an emphasis on ion implantation techniques, while I was interested in the limits of geometrical optics. However, my new University programme demanded some course work, so I attended his postgraduate materials science course and found him to be a remarkable teacher.

In 1980, I was invited to Jak's home and met his daughter Karina, a student in English and Archaeology Sydney University. We both graduated in 1980 and were married in 1983. Karina went on to forge a career in TV at SBS, Channel 7 and science broadcasting at the

ABC, and I moved to the University of Sydney Department of Applied Physics, run by Richard Collins under Head of School Harry Messel. Both Karina and Jak were to become Presidents of the Royal Society many years later, with Karina masterminding the move of that Society from Macquarie University to Sydney University and Jak being made a Fellow of the Society late in his life.

An Unwelcome Project

Upon landing in the University of Sydney in 1981, I found myself in a very materials-oriented group, justly famous for developing evacuated solar absorber tubes using spectrally selective coatings under very capable experimental researchers like Brian Window, Jeff Harding, David McKenzie, and the theorist Ross McPhedran. I became interested in using such tubes to develop simple solar collectors with non-tracking mirrors, but enough optical concentration to be capable of producing high temperature steam for electricity generation industrial thermal applications. However, to generate power efficiently, we would need more a efficient absorber coating than had so far been developed.

In 1952, an Israeli Researcher Harry Tabor had shown that it was best to design solar absorber surfaces that are highly absorbing (black) in the short wavelength solar spectrum to maximise the absorption of solar energy, and highly reflective ("silvery") in the long wavelength thermal re-radiation spectrum because highly reflective surfaces emit very poorly, so minimal heat is lost (Fig. 1). Tabor designed such a surface called Chrome Black, which was used for many years by the solar water heater industry, but is no longer produced because of environmental concerns about the heavy metal Chromium.

The general view by the early 1980s was that selective coatings were not likely to function well at higher temperatures required for thermal power generation, about 500°C. Jeff referred me to recent papers by D. M. Trotter and A. J. Sievers (1979, 1980). Solar wavelength selective absorber coatings turned out to be a very active topic with hundreds of papers being published every year. For a non-specialist in materials, it was daunting and I had a lot to learn.

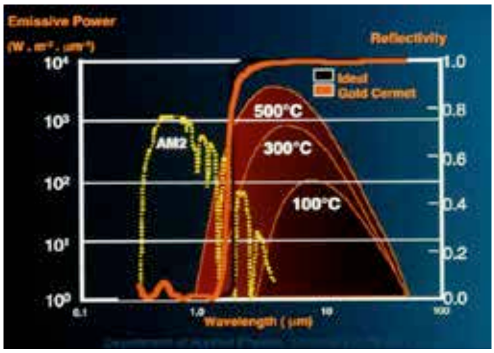


Figure 1: A diagram of the solar selective coating action taken from the author's presentations in the early 1990's. AM2 is the solar radiation spectrum and mountain like wave forms to the right are spectra for black surfaces at different temperatures. The "ideal" selective absorber surface is shown in black and rises from 0% reflectivity to 100%. The vertical section of the line is called the 'edge'. Complete separation of the solar and re-radiation spectra is impossible, but a near-vertical edge maximises solar collection and minimises thermal loss. Real surface edges produced back in the 1980's were not very vertical and were situated at about 2 microns wavelength.

My department head Richard Collins was of the view that solar systems only had value at low temperatures such as for water heating and perhaps process heat and refrigeration. Having come from a nuclear energy background, he was in favour of nuclear systems for electricity generation.

My ignorance of the materials field caused me to ask questions that others found trivial, but I found some interest from a colleague in the School, Lindsay Botten. I increasingly felt that the conventional 2 micron edge position seemed more like an article of faith than an optimal positioning. In 1983 we published a paper (Mills and Botten, 1983) which suggested that the position and steepness of the edge were critically important to performance. We showed that if we changed the edge position to below 1.8 microns and made it steeper, the ratio of energy absorbed to energy lost could be much improved up to 700°C, well into the realm of high temperature thermal generation. We suggested a surface called the "SIM" and composed of three layers, a semiconductor layer atop an insulating dielectric layer, with a reflector layer at the bottom. The top layer would be more porous going upward so as to better match the refractive index of the air above it and thus reduce reflection losses. The paper noted that "*Selective surfaces of the SIM type would....require concentrations of ~6-7 times at 500°C and ~25 times at 700°C. The former figure can be attained by relatively inexpensive non-tracking adjustable concentrators, while the latter tracking parabolic trough arrays.*"

However, there were no such 'steep edge' surfaces yet available. Two years later I published another paper (Mills, 1985) that refined the theoretical analysis and suggested a possible approach that might be able to use SIM Germanium or Silicon-Germanium cermets (ceramic metal mixtures) as a basis for surface coating with very low emittance. Unfortunately, our Department Head remained strongly opposed to developing high temperature solar energy for electricity production. In a conference paper (Collins, 1986) he wrote that[i]

"The intrinsic nature of the [renewable] resource make it uncompetitive with fossil fuels in most applications."

and

"*Society is unlikely to be dependent on renewable energy in a major way in Australia for many decades, even centuries.*"

It didn't look promising. Clearly, I would not be able to count on Departmental financial or infrastructure support to get this idea to the experimental stage. Fortunately, my non-permanent position continued to be supported by School Head Prof. Harry Messel, who presciently saw value in the work. However, this much appreciated encouragement did not extend to funds for the research. I needed a way to develop the project basics without using departmental resources or even intimating a link to high temperature solar.

The D&D Grant

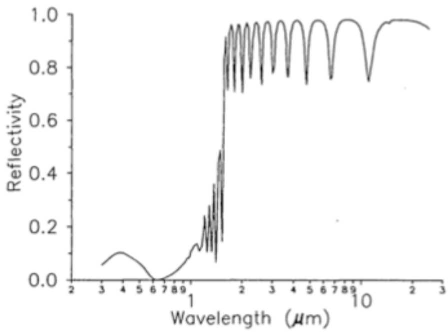
As I had done previously when problems arose at the UNSW, I dropped over to my old department and discussed the situation with Jak Kelly. Quite by chance, I had just come across a paper about ion implantation forming waveguides of germanium oxide in germanium. I asked Jak if ion implantation could be used to allow the production of optical layers of Si/Ge within a dielectric matrix so that information on optical constants might be obtained. He said it could. We began to wonder if there was a workaround for the financial problem. Jak expressed sympathy for my political problems and suggested that we might be able to do some basic experimental work at his UNSW lab in a joint project. We sketched out a joint project with Jak as a lead researcher. It would be a grant for basic optical studies of layers deposited by an ion beam machine. That came under basic science funding rather than energy funding, and incurred no costs in my Department except some of my time. Jak wanted to involve an unusual scholarship student from China called Qi-Chu Zhang. Zhang had survived the Cultural Revolution, was older than I was – about 40 – and had a long background in materials experimentation.

Jak and I jointly applied to the Australian Research Council, and our project, *Ion Implanted Optical Multilayers* received exactly $82,059. Karina was amused by it all and nicknamed it the "Dad and Dave Grant" in homage to the 1930's radio soap opera and later films. We were also successful in a follow-on grant that took the project to 1989. As a first step, the project developed surfaces based on pure Germanium instead of the preferred Si-Ge mixture, and the UNSW part of the team demonstrated very favourable absorptance in the surfaces that was unexpected according to current theory (Zhang, Kelly and Kenny, 1990). By 1989, Jak was approaching retirement and the money was drying up, but by then encouraging lab results provided enough justification for me to apply for NERDDC (energy research) funding, with the research to be carried out back at my base in Applied Physics at Sydney University using sputtering deposition equipment in that department.

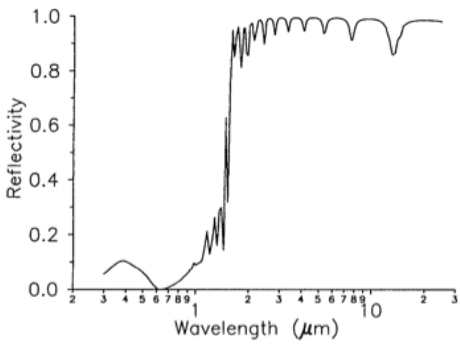
The new grant now clearly emphasized the intention of producing surfaces for a new generation of more efficient and higher temperature solar evacuated tubes. This time there was no opposition; parabolic troughs with chrome black coatings inside evacuated tubes had started to be used in California for thermal operation just above 300°C. Similar systems with more efficient tube coatings should be able to achieve 500°C. The grant application was successful and the project was called High Temperature Solar Evacuated Tube and provided $96,705. I duly hired Zhang immediately after he had successfully completed his doctorate.

The initial emphasis of our project was on developing Germanium-based SIM surfaces using the Sydney University sputtering equipment, and then moving to sputtered Si-Ge surfaces which might yield a better-placed edge position. The first sputtered results were excellent with the deposited surfaces having very low thermal loss by emittance. Fig. 2 shows a comparison of modelled and experimental data from the work. The measured and calculated reflectivity curves were similar for a layered structure of a Ge and GeO_2 mixture on Ge on a Cu substrate shown in Fig. 2(a) and 2(b), and the surface experimental worked optically very well, with an emittance of 0.073 at 500°C, much lower than previous surfaces in the literature. Zhang was able explain the results using experimental optical constants he had measured and theoretical improvements derived in his PhD thesis.

The original SIM surface concept was finally validated, as was Zhang's newer modelling. We were of course, very happy.



(a)



(b)

Figure 2: Modelled (a) and experimental (b) reflectivity spectra of SIM Ge/GeO$_2$ *surfaces on a Cu substrate. Note the very steep edge behaviour. These figures were are from Zhang, Kelly and Mills (1991). The conference paper published in 1991 included Jak's name as a co-author in recognition of his extensive work with Zhang on earlier ion beam samples which was reported.*

But science rarely runs exactly to plan; just the act of investigating something in great detail often produces more than you had ever imagined. I had purchased a faster desktop computer for Zhang's modelling and during a delay in the delivery of Ge material, he used his new machine to perform more than 1000 runs using his methodology, allowing optical constants and surface thicknesses to be varied to converge on an optimal optical configuration. It was a brute force calculation that took many days, but the result was a big surprise.

Germanium was very expensive and the SIM layers were relatively thick (about 2 microns), increasing sputtering time greatly. What Zhang showed me were modelled surface performance results that approximately equalled the performance of an SIM surface, but used much thinner layers. Furthermore, the new surfaces did not employ expensive thick semiconductor layers at all. The new layers could be made by co-sputtering common inexpensive metals or dielectrics. The new surfaces were very different; instead of a gradual variation in refractive index in the top layer to promote high solar absorption, as was standard in the field, the new surface used two very thin homogenous cermet layers, each with a different refractive index as illustrated in Fig. 3.

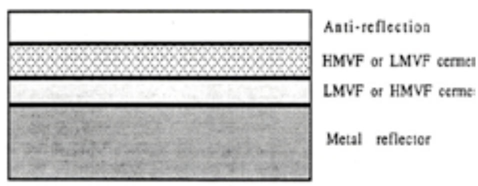


Figure 3: The new film structure was composed entirely of homogeneous layers. From the top downward, a thin anti-reflective coating using a low refractive index material is followed by two cermet layers of differing refractive indices and then a reflective layer underneath. It didn't much matter whether the high metal volume fraction (HMVF) cermet layer was above or below the

low metal volume fraction (LMVF) cermet layer; the refractive indices could be adjusted to make them work similarly. It was also found that three cermet layers could improve performance slightly, but would probably not be cost-effective, and four or more gave no improvement. The figure is the original from Zhang and Mills (1990).

We hadn't finished our Ge work, but we knew this discovery was very important. I applied to NERDDC to change the technical direction of the project and the funders agreed that the new surface should be a better candidate for low cost high volume production.

The new surface was named the "Double Cermet" coating and it was first announced at the Conference of the Australian and New Zealand Solar Energy Society (Zhang Kelly and Mills, 1991), followed by a paper in Applied Physics Letters (Zhang and Mills, 1991a) and later papers (Zhang and Mills, 1991b, 1992 and 1996) as the idea developed.

Fig. 4 shows calculated and experimental reflectance spectra for a surface using Cu-SiO2 cermets on a Cu reflector layer. The steepness of the edge in Fig. 4 is apparent; it could be improved further as well, as shown by the gold line in Fig. 1 for a later experimental surface using a gold reflector layer. Many variants of the surface were prepared in the lab and a practical sputtered version using stainless steel carbide cermet became popular for commercial water heating applications.

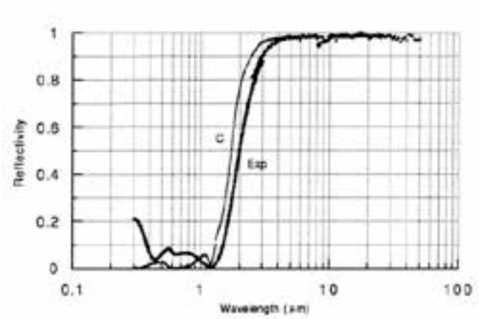


Figure 4: The experimental absorption and emittance of 0.911 and 0.0594 compared quite well with an ideal surface (edge at 1.8 micron) having values of 0.959 and 0.0275, and the double cermet emissivity was lower than the previous Ge/GeO surface value of 0.073. The small absorption reflectivity in the visible shown decreases absorption compared to the ideal of zero, and the experimental surface edge was closer to 2 rather then the desired 1.8, but the results are is reasonable agreement. This figure is from Zhang and Mills (1991).

A Fortunate Intervention

The double cermet surface and other university evacuated tube technology were licensed to the Chinese companies Turbosun in 1996 and Himin in 2004. The technology soon spread to other companies in China. Today, the number of evacuated tubes produced each year in China for hot water is in excess of 100 million, and many premium tubes use the double cermet surface. Well over 100 million people use Sydney University-derived solar hot water systems, which in China had a thermal capacity of 118,000 MW in 2012. A large number are now imported to Australia for water heating as well.

In addition to hot water applications, the double cermet surface coating provided a new inspiration for coatings used in high temperature evacuated tubes for parabolic trough and linear Fresnel systems developed in the last decade, as we had hoped in the 1980s. Parabolic trough collectors now use evacuated tubes with temperatures of operation of 500°C, and even higher temperatures are now being investigated. Their spectrally selective absorber coatings use additional adjacent anti-diffusion layers to preserve the integrity of the basic surface structure at such temperatures, but optically they operate similarly to the 1991 laboratory double cermets. Trough concentrating mirrors provide in excess of 25 times concentration, higher than we suggested in early days, but the commercial surfaces used aren't quite as efficient as the theoretical surfaces that we proposed back in 1983 and 1985 so higher concentration is needed at 500°C Whatever the reflector system, high temperature selective coatings in evacuated tube receivers have become commercial reality. It is extraordinary to think that such a tiny team not only solved the seemingly intractable problem of how to make high highly selective solar absorbers once, but twice.

Looking back, the important decision by Jak Kelly to host development at a critical time in undoubtedly saved the project. Jak was a nuclear fusion advocate in his later years, but his almost limitless enthusiasm embraced many fields. In this solar project, his immense experience in materials science, provided excellent guidance and an ideal experimental platform for his brilliant PhD student, Qi-Chu Zhang. Even though Jak was not directly involved in the later double cermet work, the UNSW-based ion beam effort proved a firm grounding for the Zhang's later computer simulation and experimental work using sputtered surfaces at the University of Sydney.

Zhang later returned to China as the CSO of Himin and oversaw for many years the development of that company's tube coating facility. He is semi-retired and remains a citizen of Australia. His family live in Sydney.

Jak passed away in 2012, but lived to hear of the impressive commercial results of his timely contribution and was always very chuffed that many millions of people were using this low thermal emissions technology every day.

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The Development of Modern Particle Accelerators at the Stanford Linear Accelerator Center

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Abstract

The development of high-energy accelerators at the Stanford Linear Accelerator Center has closely paralleled the advances in high-energy physics over the last fifty years. From its original conception as the world's largest linear accelerator for fixed target experiments, the facility evolved over the years with various colliding beam configurations in the quest for higher collision energies. An offshoot of the high-energy physics program was the synchrotron radiation from accelerators that proved a useful tool for x-ray studies. Photon science has since become the major thrust of the laboratory with the construction of LCLS, the world's first free electron x-ray laser.

Introduction

Particle accelerator technology had already developed to a sophisticated level by the time the Stanford Linear Accelerator was proposed in the late 1950's and early sixties. The origins of the particle accelerator and the desire of physicists to study the behaviour of fundamental particles beyond that revealed in cosmic rays and the emissions from natural radioactivity have been extensively chronicled in the past. This review focuses on those developments that took place at the Stanford Linear Accelerator Center (SLAC) and how they have led to the rise of *The Standard Model*, the birth of new accelerator technologies and the burgeoning of synchrotron radiation physics that followed.

Figure 1: Aerial view of SLAC nestled in the Stanford foothills, highlighting some of the accelerator facilities. (SLAC photo)

Figure 2: The Cockcroft-Walton accelerator that was moved from the Australian National University to the Physics Department at the University of New South Wales where it was used by Jak Kelly. It is an example of an early high-voltage accelerator. (ANU photo)

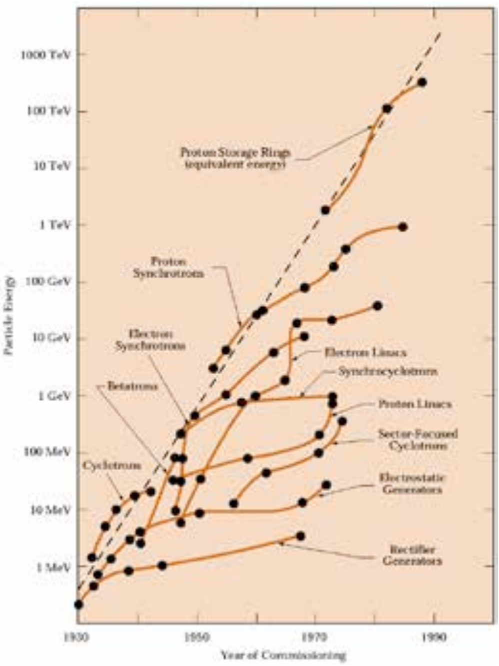

Figure3: A plot, styled after Livingston of the change in accelerator technology that allowed accelerators to increase in energy.

The machines at SLAC, shown in Figure 1, have always been used to accelerate electrons, or their antimatter counterparts, positrons. The dogged adherence to lepton machines is based on the premise that leptons are a point-like particle, with no constituent parts and therefore the study of collisions with leptons should be the least ambiguous to interpret. While other high-energy physics laboratories delved into the complexities of protons and the structure of even heavier nuclei in ion beams, SLAC made the first of its Nobel Prize winning discoveries to support its original premise: the discovery, described in more detail in the following sections, demonstrating that protons and neutrons were indeed made of smaller, constituent parts, quarks, and that only an electron beam could reveal that fine detail.

Figure 4: A view inside the two-mile SLAC accelerator tunnel showing the linac mounted above the alignment light pipe.

The driving technology behind the SLAC accelerators is the use of very high power radio frequency (RF) fields. The earliest

Figure 5: The SLAC linac structure is shown in a cutaway view and comprises roughly 80,000 copper cells.

accelerators used dc voltages to accelerate a particle just once across a fixed potential, as in Figure 2, but the energy is limited to a few MeV before high voltage breakdown becomes a problem. High energies can only be achieved by repeated application of a time-varying electric field. The successful confluence of high power microwave technology in the development of klystrons at SLAC together with particle accelerator design put SLAC at the forefront of high energy physics.

The quest for higher energy accelerators is driven by both the need to resolve smaller detail and to be able to create exotic new particles of heavier mass out of the collision energy. In the wave-particle duality view of nature a higher energy particle beam has shorter wavelength and therefore can probe smaller detail in scattering experiments. The mass-energy equivalence tells us that the mass of any new particle created in a collision is limited by the centre-of-mass energy available in the collision.

The early high voltage acceleration technique would only ever be used at SLAC to power the electron gun used to inject electrons into the main linear accelerator (or linac, as it is commonly abbreviated). The electrons in the SLAC linac, Figures 4 and 5, are accelerated instead by high frequency waves using a technique pioneered by William W. Hansen at Stanford. The microwave power is delivered by klystron tubes, Figure 6, also developed at Stanford by the brothers Russell and Sigurd Varian.

The Early SLAC Linac

The physics motivation for building a 20 GeV electron linac was born out of the success of Robert Hofstadter's experiments on the elastic scattering of 188 MeV electrons. The experiments were performed on the main Stanford campus in the Hansen Experimental Physics Laboratory using the University's 220-foot long Mark III electron accelerator. These Nobel Prize winning experiments determined the precise size of the proton and the neutron and provided the first reasonably consistent picture of the atomic nucleus.

Figure 6: Cutaway view of one of the 240 S-band klystrons delivering up to 65 MW each of peak power at 2856 MHz.

A team in the Stanford Physics department, led by Wolfgang "Pief" Panofsky envisaged a machine 100 times larger that was destined to reveal not just the structure of the nucleus,

Figure 7 Whimsical view of the SLAC linac as depicted by Bob Gould the chief civil engineer during the construction phase.

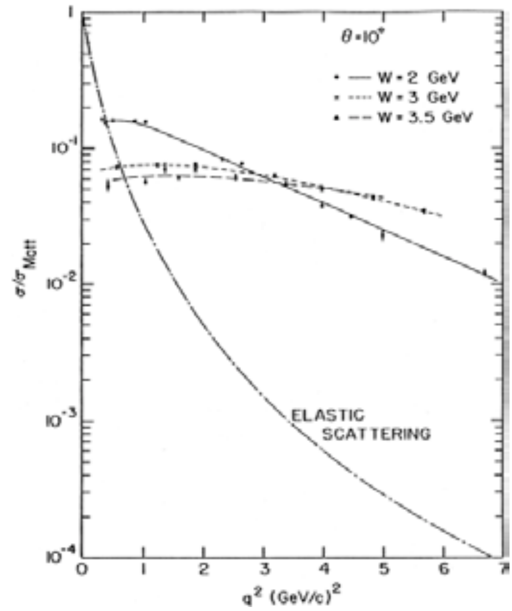

Figure 8: Evidence of the quark structure came from the ratio of deep inelastic scattering (DIS) cross-section of electron scattering in hydrogen to the theoretical Mott scattering cross-section from a point charge, plotted as a function of the square of the four-momentum transfer. The elastic scattering cross-section is plotted for comparison. (From Hoddeson et al., Fig 32.2.)

but of the nucleons themselves. Dubbed Project M, where M stood for monster, it was completed in 1966 at a cost of $120M and represented the largest publicly funded, pure research project of its time.

The project was not without controversy and caused a split in the Stanford Physics department because some of the faculty believed that the accelerator facility should be for the exclusive use of Stanford research departments. Panofsky, on the other hand believed that such a large facility should be open to the public, and invited proposals from around the world to participate in experiments at SLAC. A separate SLAC faculty was created and the two Departments went their separate ways.

The early experiments at SLAC were designed to extend elastic scattering of electrons from the proton and the neutron (in the deuteron) to higher energies, and then to extend this work to inelastic scattering, leading to the known "resonances" or excited states of the nucleons, essentially extending the previous work of Robert Hofstadter to much higher momentum transfers. However, there was a growing interest in explaining the "strange" behaviour of new particles discovered at other laboratories and the conjecture by Gell-Mann and Zweig that nucleons were combinations of "quarks" of charge ± 1/3 or ± 2/3. The new research groups began examining "deep inelastic scattering" (DIS) which left the nucleons fragmented in a continuous set of energy states. The results had tremendous implications since the DIS cross-section turned out to be much larger than previously believed. The ratio of DIS, as a function of the momentum transfer to the nucleons, to scattering from a charged point particle,

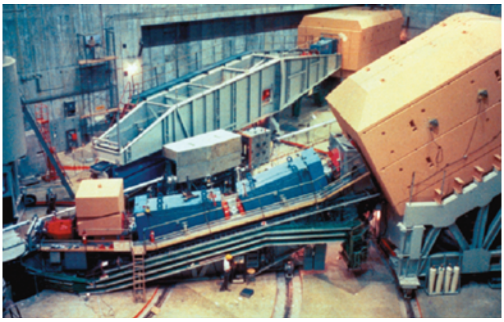

Figure 9: View of the End Station A spectrometer and detectors used to measure scattering from quarks within the proton and neutron. The scale is apparent from the human figure in the centre foreground.

exhibits a very slow variation, shown in Figure 8, is in contrast to the very steep decrease with momentum transfer exhibited by elastic scattering.

The scattering experiments required the detectors to be moved through large angles to observe both the forward and back-scattered electrons. For 20 GeV electrons the spectrometer magnets are formidable and resembled locomotives on tracks, as seen in Figure 9.

Richard Taylor, Henry Kendall, and Jerome Friedman received the 1990 Nobel Prize in Physics for this work, which established the foundation of the physical reality of the quark components of the Standard Model.

Colliding Beams at SLAC

In striving for higher energies to extend the reach of scattering experiments, one must realize that the centre of mass collision energy, E_{cm}, is reduced by the recoil of the target atom of mass m_t.

$$E_{cm} = \sqrt{2m_t E_1}$$

whereas much higher centre-of-mass energies can be attained by colliding two beams of energy E_1 and E_2.

Figure 10: The Princeton-Stanford Colliding Beam Experiment used a figure eight configuration to collide 500MeV electrons.

$$E_{cm} = \sqrt{4E_1 E_2}$$

The colliding beam concept was first envisaged for hadron machines but was soon taken over by the lepton community. Unlike protons, an electron will radiate away its energy if made to follow a circular path, and this dissipative process causes the electrons to naturally converge to the axis of the beam pipe. This makes the injection process into an electron storage ring much easier.

Several design proposals were made around the world using counter rotating beams of oppositely charged particles that could economically make use of one vacuum chamber in a single ring. The availability of an electron linac to inject the beams made Stanford an obvious choice for a demonstration experiment. An electron storage ring was proposed at Princeton by Gerry O'Neil in 1956 and the Colliding Beam Experiment (CBX) began construction in 1959 at Stanford. The figure-eight ring, shown in Figure 10, collided 500 MeV electrons with currents up to 50 mA in each beam.

Figure 11: An early photograph of the SPEAR storage ring before it was surrounded by synchrotron radiation hutches.

The CBX revealed three major limitations that would prove essential in future storage ring design. In spite of being the largest ultra-high vacuum system constructed for an experiment, with a base pressure of 10^{-9} Torr in the 2 m^3 volume, the pressure would rise by a factor 300 when higher beam currents were stored. Desorption from synchrotron light impinging on the chamber walls caused a pressure spike that severely limited the stored beam lifetime. The synchrotron light power scales as the 4th power of beam energy and required a re-evaluation of the vacuum system design.

The second limitation observed during operation was a transverse resonant instability caused by the image charge wall currents causing wakefields in the vacuum chamber. Resonant coupling could be suppressed by separating the betatron tune of the two rings, and further damping was observed due to rest gas ionization effects.

The fundamental limit affecting all future storage rings was found in the beam-beam tune shift, $\Delta\upsilon$. This is the transverse focusing of one beam upon the other and increases as the interaction density, or luminosity, increases according to

$$\Delta\upsilon_y = \left(\frac{N r_e}{2\pi\gamma}\right)\frac{\beta_y^*}{\sigma_y(\sigma_x + \sigma_y)}$$

for N electrons at an energy $E=\gamma m_e c^2$, with transverse beam sizes $\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$, where $\beta_{x,y}$ are the lattice functions, $\varepsilon_{x,y}$ the beam emittances and r_e the classical electron radius. Tune shifts above 0.025 typically caused beam degradation and loss of luminosity due to resonance induced by the beam-beam interaction.

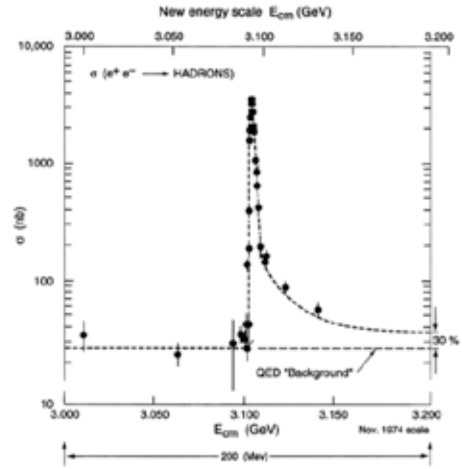

Figure 12: A historic plot marking the discovery of the J/Ψ particle at SPEAR.

The lessons learned proved invaluable for future storage ring designers, particularly one collaboration member, Burton Richter who went on to lead the effort to design the Stanford Positron Electron Asymmetric Rings (SPEAR). This collider began operation in 1972 and proved to be the most prolific of all the SLAC accelerators in providing physics results per dollar spent on their construction.

At the time of its inception, the SPEAR project was competing with more conservative upgrade projects that would raise the main linac energy by at most a factor two. These projects eventually also proved successful and led to the success of the linear collider described in the next section. However, the physics motivation of being able to raise the centre-of-mass energy by an order of magnitude over the CBX machine was enough to spur the laboratory management to fund the SPEAR construction out of operating funds without obtaining direct government funding agency approval.

Funding was not available for a new building to house the new machine so it was literally constructed on the parking lot adjacent to End Station A and covered over with concrete radiation shielding blocks, as seen in Figure 11. The design was simplified to a single ring with counter rotating electron and positron beams of 3 GeV energy. Unlike the electron-electron collisions in CBX, the e^+ and e^- can annihilate each other producing an intermediate state with enough energy, and according to conservation laws, to spontaneously produce massive new particles. Studying how these particles are produced proves to be the ideal tool for learning about their structure.

The gamble paid off handsomely with the observation of a resonance in the event rate at a centre-of-mass energy of approximately 3.1 GeV, shown in Figure 12. This was attributed to the production of a new particle the J/Ψ which could only be explained as a tightly bound pair of charmed quarks. The laboratory director announced the discovery to the Atomic Energy Commission with the statement: "I would like to report the discovery of an unauthorized particle on an unauthorized colliding beam facility". In 1974 it heralded what is now referred to at SLAC as the November Revolution. The discovery resulted in a Nobel Prize for Burton Richter and Samuel C. C. Ting, and was followed by a rich study of charmonium physics revealing the spectroscopy of various bound states of charm-anticharm quarks.

Figure 13: A view inside the PEP tunnel showing two rings stacked on top of each other for the PEP-II asymmetric B Factory.

The SPEAR ring yielded yet another Nobel Prize to Martin Perl for his discovery of the tau lepton, the third of the three families of leptons, the electron, the muon and the tau.

At this point in SLAC's history funding became available to build upon this success and construct an even larger collider, the Positron Electron Project (PEP) able to attain 15 GeV with a ring 1.4 miles (2.2 km) in circumference. This was the largest ring that would comfortably fit on the SLAC site. A large ring is necessary at high energies because the energy loss per turn due to synchrotron radiation increases as the 4^{th} power of the energy while it only decreases linearly with machine radius.

During the PEP era at SLAC Burton Richter spent a sabbatical period at CERN in Switzerland where he entertained the idea of designing the maximum energy storage ring feasible on an unlimited site. CERN went on to build the Large Electron Positron project (LEP), a 27 km circumference ring capable of attaining 50 GeV beam energies.

Three Families of Matter		I	II	III	*H* Higgs boson	
Quarks	+2/3	*u* Up	*c* Charm	*t* Top	γ photon	Force Carriers
	-1/3	*d* Down	*s* Strange	*b* Bottom	*g* gluon	
Leptons		*e* electron	μ muon	τ tau	*Z* Z boson	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	*W* W boson	

Table 1: The Standard Model can be thought of as a type of Periodic Table from which all the known sub-atomic particles can be constructed.

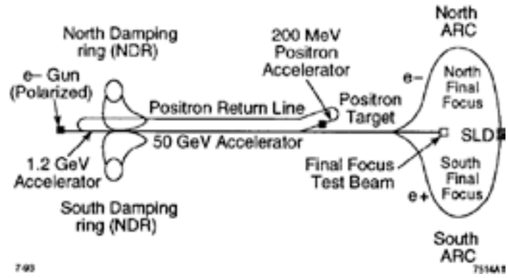

Figure 14: The SLAC Linear Collider accelerated bunches of electrons and positrons to 50 GeV which were deflected in opposite directions around an arc to collide at the detector.

Richter, on the other hand, returned to SLAC proclaiming that we must return to linear accelerator technology for colliding beams in order to overcome the energy limitations of storage rings.

Before turning our attention to the linear collider project at SLAC we should jump ahead to SLAC's final endeavour with storage rings, and the construction of an asymmetric collider known as the PEP-II B-Factory. Two rings were constructed inside the PEP tunnel, stacked one on top of the other, as shown in Figure 13, to store 9 GeV electrons in the high-energy ring and 3.1 GeV positrons in the low-energy ring, with one intersection point where the beams would be allowed to collide. The rings began operation in 1999 and eventually reached a luminosity of around 10^{35} cm^{-2} s^{-1} at astonishing beam currents of approximately 1.5 A of electrons and 2.5 A of positrons.

The centre-of-mass collision energy was tuned to the Upsilon 4S resonance to produce a flavourless meson formed from a bottom quark and its antiparticle that then decays into a pair of B mesons. It allowed the first observation of charge-parity violation outside of the kaon system and helps explain why at the instant of the Big Bang, the mechanism by which there is more matter than antimatter in the universe. A key factor in these observations was to make the collisions asymmetric in energy so that the centre-of-mass frame would be moving during the collision and allow the lifetime of the different decay channels to be identified by virtue of the distance of the new particle vertices from the collision point.

The SLAC Linear Collider

The discoveries at SLAC gave strong support to the quark model, and the "eight fold way" was enhanced to become "The Standard Model" and is summarized in Table 1.

The quarks and the leptons appeared to be divided into three families of matter and all the particles that had been discovered at SLAC and elsewhere could be accounted for in this framework. The vector bosons in the Standard Model, or force carriers had also been observed. The next step was to confirm that there were indeed only three families of matter, not more, and this could be confirmed by measuring the resonance width of the Z boson, the carrier of the weak force. Both CERN and SLAC proposed the construction of an e^+e^- collider with a roughly 100 GeV centre-of-mass energy at the Z_0

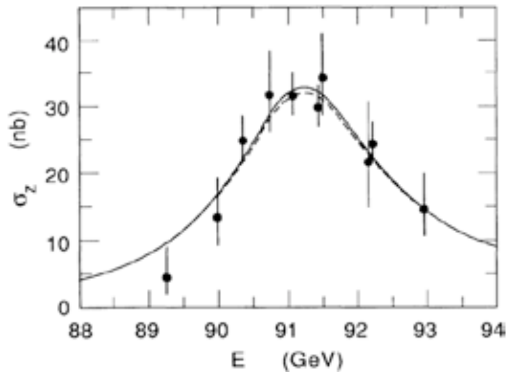

Figure 15: The SLAC measurement of the width of the Z_0 resonance at 91.4 GeV confirmed the Standard Model prediction that there were only three families of matter.

resonance to make this precision measurement. CERN proposed the 27 km LEP ring, and SLAC proposed using the 3 km long linac to reach the same energy. SLAC was able to raise the energy of the linac from its original 20 GeV to 50 GeV through the invention of the SLED device (SLAC Linac Energy Doubler). It uses RF pulse compression to deliver four times the peak RF power in a shorter pulse to the linac structure thereby increasing the accelerating field gradient.

SLAC would have to perform an extra trick of accelerating consecutive bunches of electrons and positrons and deflecting them around two opposite arcs, as shown in Figure 14, to bring them into collision in the centre of the SLD detector.

The LEP storage ring would collide the bunches ten thousand times per second as they went round and round, so the SLAC Linear Collider (SLC) would have to focus the beams to micron size diameters in order to get the same luminosity in the detector. This was possible at SLC by making very small emittance beams in the damping rings and then keeping the emittance under control as the beam was accelerated in the linac.

The storage ring was a more conservative approach and ultimately reached a higher luminosity, but the linear collider was also a test experiment for future colliders. Clearly, the next generation of colliders operating at 10^{12} or Terra electron volt (TeV) energies would be impractically large if built as rings, so it was important to test the linear collider concept whose size would still be manageable when scaled to a TeV.

The SLAC measurement of the Z_0 resonance, shown in Figure 15, was still sufficient to prove beyond a doubt that the Standard Model held true and that only three generations of matter could exist.

Synchrotron Light Sources

Already during the heyday of particle physics at the SPEAR machine another group of Stanford physicists was lobbying for access to the photon radiation generated by the beam circulating in the ring. Synchrotron radiation was regarded with disdain by the machine builders because it limited the energy of a storage ring and it produced unwanted heating and outgassing of the vacuum chamber. The photon users persisted with their claims that the synchrotron light was the brightest source of x-rays in the world, by orders of magnitude, and would allow revolutionary new science to be done.

The director of SLAC reluctantly allowed one photon beam line to be added to the SPEAR ring, worried that it would take away precious beam time from the high-energy physics program. The rest is history, as they say, and the number of synchrotron radiation beam lines grew rapidly. When SPEAR reached the end of its useful life as a high-energy physics machine it became the world's first dedicated

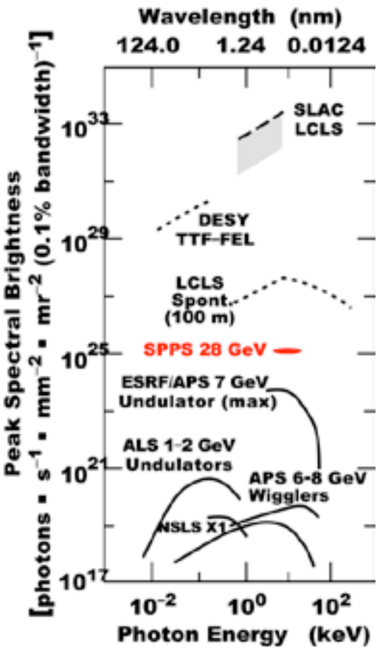

Figure 16: The peak brightness from linac-based light sources exceeds storage rings by many orders of magnitude over a range of wavelengths.

synchrotron light source. It has been upgraded several times and still operates today as a 3rd generation light source, SPEAR3.

Many dedicated synchrotron light source laboratories have now been built around the world, numbering more than sixty, including the Australian Synchrotron built in 2007 in Melbourne. These modern storage rings use *insertion devices* to wiggle the beam in an undulator section to produce extremely bright x-ray beams. The brightness of the x-rays is ultimately limited, though, by the equilibrium electron bunch dimensions in the storage ring.

The light source designers enviously looked at the extremely small electron bunches that the linear collider was producing and calculated they could create a free electron laser (FEL) at x-ray wavelengths using a very long undulator

Figure 17: view of the 100 m long undulator of the Linac Coherent Light Source.

at the end of the linac. The linear collider project was not about to give up any of its precious beam time to the light source users, but we were able to do a proof-of-principal experiment to demonstrate the feasibility of x-ray production with the linac.

An electron bunch compressor chicane was installed in the linac in 2002 which would compress the bunches to a pulse as short as 80 femtoseconds duration. The bunch compressor chicane worked by putting an energy *chirp* on the electron bunch, giving the head of the bunch a higher energy, and then sweeping the bunch around a chicane so that the low energy tail would catch up with the head of the bunch.

A 2.4 m long undulator borrowed from the Argonne Advanced Photon Source was installed on a beam line at the end of the linac and the compressed 28 GeV electron bunch produced a blinding flash of x-rays at 1.5 A wavelength.

At this time the linac was primarily being used as an injector for the PEP-II collider, but it was possible to parasitically deliver 10 Hz repetition rate beams to this new photon facility, the Sub-Picosecond Photon Source (SPPS). Numerous experimental techniques

Figure 18: The LCLS undulator is made up of thousands of permanent magnet wiggler magnets.

for linac-based light sources were able to be tested with the ultra-fast pulses at this facility.

For a time the SPPS held the record for peak brightness for any x-ray source, as seen in Figure 16. The radiation, however, was still incoherent, as it is in storage ring light sources. The bigger prize was yet to come with the installation of a linac-driven FEL.

The Linac Coherent Light Source LCLS

The LCLS produced its first x-ray beam in 2009, and uses a 100 m long undulator, shown in Figure 17, at the end of the linac to produce Self Amplified Stimulated Emission (SASE) at x-ray wavelengths. The undulator is assembled in 3 m long modules made up of hundreds of permanent magnet dipoles, as shown in Figure 18. The incoherent synchrotron radiation generated as the beam wiggles back will amplify in one selected mode and produce fully coherent x-rays that are 10 orders of magnitude brighter than a storage ring light source.

Such an increase in brightness over existing machines has required the invention of a whole new science in analysing x-ray diffraction. It is now possible, for example, to image a single molecule in a single shot. It will no longer be necessary to crystallize complex organic molecules such as proteins in order to image their structure. Enough photons can impinge on a single molecule that the diffraction image can be collected from a single molecule. The downside is that of course the molecule does not survive the onslaught of such a bright beam of x-rays. However, the pulse duration from the LCLS can be as short as a few femtoseconds so it is possible to capture the image before the molecule flies apart. The extremely short duration of the pulse also allows ultra-fast phenomena to be captured in the strobed images. A technique referred to as pump-probe allows the molecule to be stimulated and then observed with the x-ray strobe at sub-picosecond intervals after the stimulus has been applied.

Conclusion

SLAC has had a rich history, playing a significant role in the development of accelerator technology and the understanding of modern particle physics. SLAC continues to play a role in the development of new technology for future colliders and participates in international collaborations to build a Linear Collider and Higgs factory. The SLAC campus, however, may become more recognized in the future for its role as the world's leading photon science laboratory with its unique facilities for x-ray laser production.

Acknowledgements

This article is written in fond memory of my mentor and thesis advisor, Professor Jak Kelly, who instilled in me a suitable awe for large accelerators and high-energy physics. I am happy to say that this fascination with accelerators has stuck with me at SLAC. In preparing this article I am also grateful to the SLAC Archive Office for their extensive collection of photographs and articles chronicling the history of SLAC.

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Patrick Krejcik

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Patrick Krejcik graduated from the University of New South Wales with a PhD in 1980, where his supervisor was Professor Jak C. Kelly at the High Voltage Accelerator Laboratory in the School of Physics. Jak instilled in his students not only an awe for physics, and that it could be good fun, but also that it was part of a bigger adventure that was going on in laboratories around the world. Patrick pursued accelerator research at the German heavy-ion laboratory, GSI, then at the proton-antiproton collider at CERN in Switzerland, before finally moving to SLAC in California, where he now resides.

In later years, Jak wryly observed that there was an alarming trend in Patrick's career moving from heavy ions at GSI to smaller protons at CERN, then to tiny electrons at SLAC and finally to massless photons in the FEL laser, suggesting that there may only be the vacuum energy of virtual particles left to speculate on. Jak's energy and wit remains with us.

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Paper clips, rubber bands and satay sticks

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Abstract

This is a personal article about the lasting influence the late Professor Jak Kelly has had over the course of the author's varied career. His influence was especially pronounced when the author was under pressure and had to confront a difficult and unusual situation. Some of these situations are illustrated in this article. It is hoped that the article showcases in parts Professor Jak Kelly's sense of humour. Professor Jak Kelly was a mentor and a long term friend of the author.

"*Most people say that it is the intellect which makes a great scientist. They are wrong: it is character.*" *Albert Einstein*

Introduction

The day I met Professor Jak Kelly was the day I did something that was totally out of character: I declined an offer to have graduation drinks at the 'White Horse' with fellow students from Sydney University. Instead, I headed to the School of Physics at UNSW to enquire about a teaching position with postgraduate research work. In those days it was a 'buyers market'. You went around to all the departments, had a chat with the Heads and then decided which group to join. On first meeting, Jak was enthusiastic and passionate about science. He also seemed to have a wicked sense of humour and the research work he was engaged in was of a vision with an exciting and useful future. The decision to join his group was a foregone conclusion when he took me to view the impressive 1.25Mev Cockcroft-Walton accelerator, standing a storey high inside a former Electrical Transformer Building.

Every Friday afternoon Jak made it a focus for all his postgraduate students to gather together on the grounds of the Accelerator to present our progress of the week. We discussed problems we had encountered and freely shared ideas. These discussions were always accompanied by great food and increasingly better quality wines. It was at these meetings with Jak and fellow students that Jak inspired in me to look at the world not just with a scientific eye but with a broad vision; to try to think differently, to challenge accepted dogma, and to consider historical perspectives. Jak's great strength and drive was to apply ideas across many disciplines. Jak was also a great orator and showman and his formal lectures were legendary.

Lesson 1: "Curb your enthusiasm!"

Jak valued genuine intention first and foremost. If then the result turned out disastrous his Irish humour helped to ease the pain and embarrassment.

My PhD project involved the study of sputtering. This is the process of ejection of atomic material from the surface of solids during bombardment by energetic atomic particles. The experimental setup that I used to study the phenomenon had a small oven that produced the energetic particles.

This oven was cooled by water. It was easier to connect the water to the mains than to the 2000 litre storage on the roof.

One late Saturday night, after completing a full day's experimental run, I headed home, forgetting to switch off the water cooling. I was barely awake the next morning, when I received the call, "You better come right now. The School of Physics is flooded." I was in a nightmare. It was not until I drove down High Street that I saw a triangle of water spanning two floors – at its apex, the window of my lab. After I entered the School of Physics, reality very quickly asserted itself. As I rushed in to go up the main staircase, a perfectly formed waterfront cascaded down over the stairs. On the First floor, the Head of the School's dog darted out at full speed towards me. It immediately registered the mini lake in front of it and with a terrified, desperate look in its eyes, it tried to stop. You could even pick up the Doppler shift in its desperate cry and yelp as it water-skied past me, haunches on the ground, front leg outstretched, forming a perfect wake.

Next I entered the library and there an equally surreal image confronted me: the School of Physics' librarian holding an umbrella in the downpour from the ceiling above, desperately trying to save as many books as he could. I felt bad about the disaster I caused but I felt worse about the books. They took months to dry out.

At the end of that Sunday, with as many helpers as we could muster, we managed to clean up the water. We all then gathered at the Head of School's campus residence for a beer. Jak knew that his group would receive a fine for the downpour and the damage it caused. As was his way though, he pulled me aside and said, "Zoltan, my boy, you must curb your enthusiasm!"

I believe that in the years that followed there were a few 'enthusiasts' like myself.

Lesson 2: "Have you done your experiment correctly?"

This was the question that Jak always drummed into us, even when the experimental results seemed to confirm our expectations and especially when faced with an anomalous results.

The first time I heard him ask me this question, he followed it as usual with an anecdote about the time he was working at Harwell Atomic Energy Establishment in the UK. He noticed that experimental results taken before lunch were quite different to those taken after lunch. Could it be that when he, Paul Chatterton and other members from the lab would go out to lunch, which would of course included some ale or wine with the meal, this may have somehow influenced the measurements? Jak being a true scientific sceptic, dismissed this hypothesis on the grounds that in his experience, up till then, he found that insights and experimental measurements usually were improved by a glass or two but only when not imbibed in excess of course. He then noted that not all laboratory members joined them on their usual lunch break. In fact there was a young technician, a teetotaller who never joined them. On questioning the young man, the mystery was solved when it became evident the he used the vacuum chamber to warm up his curry at lunch time. Thus the experimental anomaly was not due to the effect of wine but rather due to the left over residue from curry vapours.

After completing my PhD thesis in 1979, I worked for a brief period at Sydney Hospital with Dr Leopold Dintenfass. His interest was studying the factors affecting the viscosity and aggregation of red blood cells. He was preparing an experiment to go aboard the space shuttle 'Discovery' as at the time NASA was also interested in red blood cell aggregation under zero gravity, aggregation being the process whereby red blood cells stacks together to form linear and three dimensional structures. Dr Dintenfass, was at the time, the first Australian scientist to have an experimental project accepted by NASA. The proposed experiment used an automated slit-capillary photo-viscometer. This instrument consists of a set of two highly polished glass plates, with a gap of 12.5μm. Using an infusion pump, blood samples could be introduced into the slit-capillary. Two types of experiments were planned. The first was to take micro and macro photographs of static blood in the slit. In this case, the pump introduces the sample into the slit and then is stopped to allow for the formation of aggregates. Photographs were then taken. The second experiment was to take blood viscosity measurements. I was asked to investigate the anomalies found within these measurements.

One day when I was in the workshop with the glass polisher, I noticed the monochrome light source he had to check the flatness of the glass plates he was polishing. I instantly had a hunch. I went back to him with one of our slit viscometers and put it under the light. I used water to inject into the slit and the resultant interference pattern showed that the glass plate assembly was deforming under pressure of the liquid being injected into the slit. A quick high school calculation from the measurement of the fringes, revealed that the gap between the plates near the centre, more than doubled. The main source of the anomaly was found. Unfortunately it was too late to redesign the glass plate and assembly and to resubmit the proposal to NASA.

There were two NASA shuttle flights in 1985 and 1988 where the equipment was only used to obtain photographs of red cell aggregation. The results of both flights showed significant changes in red blood cell morphology and a reduction in the size of aggregates in native plasma.

Lesson 3: How useful is a paper clip and rubber band?

There are times when an urgent solution necessitates unorthodox methods and tools.

After working with Dr Dintenfass I was offered a contract with the CSIRO's Mineral Physics and Nuclear applications group facility in North Ryde. My work included working in the field in Western Australia, at Kalgoorlie, and at a remote station at Yeelirrie, where the nearest town, Waluna, was 70 kms away. I learned in Jak's lab the importance of self reliance and of having a detailed knowledge of your experimental equipment. These skills were paramount in my success in that isolated environment.

In 1983 near the end of my four year term with the CSIRO, I was involved with the assembly and testing of the recently acquired 2.7Mev Tandem accelerator. The accelerator was to be used as a microanalytical system in geochemical and geochronologic studies. The accelerator was thoroughly tested the night before the facility was due to be officially launched. In the control room, The Honourable Minister for Science Barry Jones was to push a big red button which would turn on the accelerator. An ion beam would be produced that travelled down inside a vacuum tube be bent around by an electromagnet. It would then travel down a straight section of the vacuum tube into a small chamber. The chamber contained a remotely controlled mechanism with a small target that would flip into and intersect the beam showing a glowing spot. This glowing spot was picked up by a video camera and would then show up on a television screen next to the red button that initiated the whole sequence. The glow was a visual confirmation that the accelerator worked.

The Minister, along with dignitaries from the Government and the CSIRO and a news crew had been invited to witness and record the event. All tested well the night before the launch but the situation changed by morning. We all showed up early and everything was working, except for the target which would not flip into the beam. We isolated the target chamber, brought it up to atmosphere, opened it, tested the remote signal all okay. I had a very careful look and used my finger to flip the target holder and noticed that a fine spring got caught in the mechanism and had twisted and finally had broken loose. There was no time to take it out and repair it. Again I drew on Jak's teachings, think the unthinkable. A paperclip and a rubber band. The shape of the paper clip was reconfigured to fit into the mechanism with a slight counter tension and the rubber band supplied the opposing tension. Within five minutes the target was working again, more smoothly than ever before. In the jubilation some exclaimed "we should patent this".

The chamber's top was quickly bolted down, the vacuum pump turned on and when its gauge showed the required vacuum had been reached for operations the final thumbs up signal was given just as everyone entered the control room. There were only three of us who knew about the fix. We quickly left the experimental hall where the accelerator and the beam tubes were housed and joined the dignitaries in the back of the throng, with our hands behind our backs, fingers crossed. Judging from the applause, as we couldn't see from the back, we figured that my "low tech" solution must have worked.

Lesson 4: How to change careers and survive

My association and friendship with Jak and his family had continued over the years. During our association Jak advised and helped me greatly in making a major shift in my career path.

I had an offer from the Department of Medical Oncology to work in Clinical Trials at Royal North Shore Hospital. Even though I knew the work would be interesting, challenging and rewarding the fact was that I was no longer going to be practising Physics. Jak helped me over some of my doubts by having faith in my abilities and by pointing out that just because he is working in another area a Physicist never stops practicing the methods and attitudes that he has been trained with. He also pointed out that succeeding and finding reward in another area is in fact the ultimate endeavour.

He was right.

The Head of the Department of Medical Oncology was Professor John Levi, who was a founding father of chemotherapy trials in Australia. He wanted someone from pure research, outside of Medicine, to help with the design of the trials, to ensure the trials' data integrity and quality and to provide help in statistical analysis of results. Software and hardware support for his Department was also a requirement.

During my first six months of probation I had a challenge that I never expected to face: a visiting doctor who was involved in a chemotherapy trial was attempting to apply 'what-if-scenarios' to the data. I could not understand this. In trials, there is always a struggle with patient recruitment. Its critical because, with small numbers, the statistical power is weak. Furthermore, the patients are usually further divided by different treatment modalities thus further diminishing the statistical power. I found that Medicine is so much more difficult than Physics because individual humans are varied in their biological responses and genetic makeup. All one can do in a clinical trial is to identify as many patient factors that may be of relevance and to then analyse the response of the cohorts. In this case there are no 'what-if-scenarios'. I explained the situation to the doctor but he kept insisting that what he was attempting to do was valid. I felt that my new career was going to finish even before it started. The doctor hadn't actually crossed the line of 'changing data integrity' but I felt very uncomfortable with his attitude. The issue of intellectual honesty never really came up in our research in Physics, since we spent so much time ensuring that we had all the factors effecting measurements identified and their importance evaluated. A measurement was only real if it could be reproduced. In clinical trials I have seen now that a statistically significant result in one trial was quite often nullified by a similar trial at another centre. Many years later, by pooling results from many centres and applying methods of meta-analysis, helped to firm up results.

In my situation with this doctor, I had no other course except to defend my stand and to ensure that the 'line' was never crossed. I kept my job and I have been with the unit now for almost thirty years, he left medicine a few years later after this incident.

Lesson 5: Unconventional Solutions

Clinical trials are now conducted by the drug companies and my interest turned to the use of information systems in Medicine.

When Internet technology began to mature in the mid 90s I rapidly saw just how useful it could be to disseminate information efficiently. In a hospital setting what was required was to set up an Intranet. I also realised that quality and version control of documents were crucial to its successful implementation. The final tool to make the process useful was software that became available to convert word processing files into HTML. If those documents were properly styled, then those styles could be turned into a linked table of contents. I was seconded to the Information Technology Department of the Hospital to lead a team to develop an Intranet as well as policies and procedures for document authoring and version control. The project was highly successful and I was asked to give a presentation of our work to the Department of Health. The night before my talk, I was going to put the final touches to my PowerPoint presentation. To turn my laptop on, I pushed on the sliding power switch located on its side. It broke. I couldn't turn the power on and to my horror, I didn't have a backup. It was at this desperate point that again the experiences and attitudes I gleaned in Jak's lab illuminated me: do not give up, examine the problem thoroughly and most of all of seek answers outside the conventional realm. There was a small opening where the switch broke that I could push some pointed tool in and possibly throw the power switch on. However in this situation, I could not use my all purpose paper-clip tool as I might short the laptop and make a bad situation even worse. Light bulb moment, a satay stick! A mad dash to the kitchen drawers and within minutes I had the laptop come alive, made a quick backup and finished the presentation and backed that up also. As the talk took place early on in the morning, I didn't have time to get another laptop. I had to use the one I had. I didn't feel too good about using a satay stick at a presentation where I knew there were going to be some senior members from Health Department of Health. Even though I came up with a working solution and practiced turning the laptop on and off so at least it looked like a smooth operation, I still thought it was tacky but there was nothing to be done.

Once again finding myself in an unusual circumstance Jak's influence helped. Next morning I turned up to give my talk. I pulled out my laptop, placed it on the lectern and made sure that my audience could see that I had used a 5 cm long transparent tape to stick two satay sticks to the cover. I could see that most people were quite intrigued. They have never seen anything quite like it.

Don't hide the facts, emphasise them.

I began my talk by explaining what occurred the previous night and how I came up with the solution. I then took one of the satay sticks and, with a confident flourish, I turned on my laptop. A few people applauded. I then asked the audience whether anyone could tell me why I had two satay sticks. "No idea? No guesses?" I teased. "Clearly …the second satay stick is for backup."

That bought the house down.

Conclusion: "People in the cheap rows, at the back, can you hear me?"

A week after my presentation with the satay sticks I was offered one of the most rewarding projects of my career. A project that would especially help all health professionals in NSW in the far flung areas of the west of the state. At the time, Broken Hill Hospital did not even have a medical library.

The Clinical Information Access Program (CIAP) was a project of the NSW Department of Health, initiated in 1997 and driven by the Clinical Systems Steering Committee. Its principal aim was to use the Internet to bring to the point of care, clinical information for all health professionals working within the NSW public health system. The clinical information and the resources was to support clinical best practice, education and research.

I was asked to make the CIAP a reality by identifying and purchasing an initial pool of data sources and associated search engines, to contact every major medical library in the state and inform them of this soon to be delivered resource, and to obtain feedback and create the web structure for delivering the information resources purchased.

The website was launched on July 4, 1997 and the year after the CIAP received the Data Management Association (DAMA) Australia Achievement Award for Excellence in Information Management and the Australian Library and Information Association (ALIA) NSW Branch Merit Award for Services to Rural and Remote Users and the Community.

After the launch one of the many emails I received from the rural doctors was, "This is the best thing that has happened since a bail of clover in a drought."

Thus, thanks to Jak's legacy, I too managed, in my own way, to get the message to the "people at the back".

Zoltan Kerestes

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Ion beams and channelling: the early days with Jak Kelly

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Abstract

This paper contains some personal perspectives of the lessons learnt during my PhD studies with Jak Kelly at UNSW. Jak was passionate about science, had boundless enthusiasm, was an eternal optimist, was an 'ideas' person and innovator, as well as a superb motivator for his students and co-workers. I owe him much for his impact on my career in science.

Introduction

I first encountered Jak Kelly as an undergraduate student at UNSW in the mid-1960s. He was clearly the most enthusiastic and passionate lecturer in my early undergraduate years. His lecturing style was decidedly theatrical and compelling. It was not a surprise to me that his daughter Karina showed much of that style in her media successes years later. During my Physics Honours year I was called up for national service. I sought Jak out for advice on whether a PhD might be a viable choice to keep me out of the army! Jak and Brian Lawn, another impressive academic member of staff at that time, suggested an intriguing topic for a PhD that brought together their individual research interests: ion channelling in Jak's case and brittle fracture in Brian's case. Jak explained that the phenomenon of ion channelling had only been discovered a few years earlier and the field was ripe for the picking. I was impressed and signed up for a PhD. The topic turned out to be a bizarre and, ultimately, an incompatible union of research directions, but more about that later.

There were four attributes of Jak that stood out during my PhD time: i) he was a fantastic 'ideas' person but I learnt early that some filtering was necessary to give a reality check and pick those directions that were feasible given our meagre resources at UNSW; ii) he was an eternal optimist and always saw opportunity in adversity; iii) he was a fabulous motivator and his boundless enthusiasm helped me face the most daunting of problems with confidence; and iv) he was a superb innovator and taught me to improvise with what was available to achieve an important research goal. I have chosen three examples or stories from my PhD time that illustrate these attributes.

The 1.2 MV Cockcroft-Walton accelerator

Part of Jak's motivation for suggesting my thesis topic, built around ion channelling, was that he was in the process (in early 1969) of negotiating the purchase of the ANU Cockcroft-Walton accelerator. As a typically naïve student, I believed Jak when he said that the accelerator should be fully running within about 6 months and I could plan to do my channelling measurements across fracture interfaces in silicon on that machine. Little did I know at that time that a suitable home for this machine had not been found, and that was only the start of the problems that needed to be solved before the machine was usable! In truth even Jak didn't realise the enormity of the task. Anyone that has worked with accelerators will know that, when they are left idle, (essential) bits are progressively cannibalised. It was no different with the ANU machine that was decommissioned in 1967. Jak managed to convince the University to buy an old tram maintenance shed opposite Randwick racecourse. It was an ideal location, with very solid walls and a ceiling high enough to house the very impressive Cockcroft-Walton accelerator shown in its glory days at ANU in Fig.1. The charging system and the three stack configuration of the machine created a sight to behold.

When the accelerator arrived at UNSW there were many parts missing and the electrical wiring, vacuum system, beam lines and data collection needed to be completely rebuilt. Undaunted, Jak set about mobilising a team to work on it. Bob Dalgleish, a very talented PhD student who had a strong electronics background from an earlier life, played a major role in finally getting it operational by the end of 1972. Alas, too late for my own PhD! Nevertheless, the accelerator was a major focus of Jak's group activity at the time and its successful installation was a huge achievement, a testimony to improvisation that brought great credit to Jak and those who worked on it.

Figure 1: The 1.2 MV Cockcroft-Walton accelerator as installed at the ANU in the early 1950s. The high voltage generator stack is at the right. A uniform voltage gradient is applied to the acceleration tube via the central condenser stack. The ion source is located in the left side 'bun' at the top of the acceleration column.

I can well remember the occasion of the first time voltage was obtained on the ion source 'bun'. We were all awestruck! Jak had to demonstrate that high voltage was 'safe' if there was no path to ground. He proceeded to climb into the 'bun', the ladder was removed and he asked Bob to wind up the voltage. I believe we reached 50,000 volts with Jak up there, his head and shoulders visible above the bun. Jak's hair was extended in all directions, like Einstein, and one of my co-students called out: 'Jesus Christ', and at that moment, to all of us, Jak was!!

Ion channelling at AAEC: the early days

Although the Cockcroft-Walton was not operational in time, not all was lost for my thesis. Jak had already established a successful collaboration with Roger Bird at the Australian Atomic Energy Commission (AAEC) at Lucas Heights and a 'channelling' beam line had been constructed by PhD student Murray Hollis. When I started Murray had not obtained any channelling data but with the help of Pat Price, a PhD student who followed on from Murray, he managed to achieve channelling in gold foils and completed his thesis by early 1969. To achieve channelling Murray needed to construct a goniometer[1] in a vacuum chamber that had 5 degrees of freedom, all controlled from outside the vacuum. It was a beast of a system and held together just long enough for Murray to complete!

Pat and I were forced to build another scattering chamber and goniometer to have any hope of further channelling experiments. I remember talking to Jak at the time and asking him how we could get a system up and running in a reasonable time. I had been doing X-ray experiments on fractures in silicon using a simple goniometer in air and wondered how this would go in vacuum with flexible angle and translation control through vacuum feedthroughs. Jak's immediate response was: 'try it and I think I have just the chamber for it'. I dusted off an ancient chamber that Jak had used years earlier at Sydney University and within two weeks we had a very inelegant looking, but workable, goniometer in a vacuum chamber that could hold a reasonable vacuum despite the lubricants on the goniometer drives. It was connected to the channelling line at AAEC and we were off and running. This was symptomatic of the type of improvisation that Jak encouraged in the group. It is a skill that has held me in good stead over my career in science.

The experiments that Pat and I did at Lucas Heights were the first Rutherford backscattering and channelling measurements in Australia. They led to papers on radiation damage build up in alkali halides (Price et al., 1973) and radiation effects in quartz (Williams and Lawn, 1973). The chamber, beam line and analysis system at AAEC remained in use until the early 1980s, servicing many other students and researchers, until it was replaced by a more user-friendly commercial system.

As an aside, Murray Hollis went off to Chalk River laboratories in Canada and returned to the ANU, and became the laboratory manager of the Research School of Physical Sciences, the very School of which I became Director a couple of years after Murray retired. Pat Price came from a sugar cane farm in North Queensland to do his PhD with Jak. He also went off to Canada on a post-doctoral fellowship, before returning to Australia as an engineer in industry.

Channelling without an accelerator: the pinhole camera

I realised about 6 months into my PhD that I was very unlikely to be able to achieve my original goal of ion channelling across a fracture interface to dynamically measure crack tip separation. I can remember the first time I went to talk to Jak about this problem I was quite depressed. I also

[1] An instrument used for the precise angular orientation of faces of a crystal with respect to some reference direction; e.g., the incoming ion beam direction.

remember coming out of that meeting totally energised and enthusiastic again. So, what did Jak say? I honestly can't remember but there was certainly no ready solution to my dilemma. That was the effect Jak had on his students: he could motivate and encourage them simply by his positive attitude and passion. What I do remember is that he gave me a paper by a French group, Yves Quere and co-workers, and said I should read it as it may lead to something useful for my project.

The said paper was in French (Quere, 1968) and described how a radioactive source (^{241}Am, which produced 5.46 MeV α–particles) could be used to obtain channelling patterns by inserting thin samples between it and a track-recording cellulose film. I discussed this paper with another of Jak's PhD students, Hans Nip, and the two of us decided to try a twist on the French method. We built a pinhole camera that is shown in Fig. 2. We figured that it could be used for observing channelling phenomena. We actually built the camera and obtained channelling patterns before we told Jak anything about it. When he saw the results he was delighted and told us that this was just the sort of innovation he wanted to see from his students. The trick with these experiments was to polish the single crystal sample to a precise thickness that was too thick for α–particles that entered the crystal in a random direction to penetrate through it but thin enough for easy penetration of well-channelled particles. The distances between sample and source (d_s) and sample and film (d_f) could be varied in our vacuum camera as well as the penetration angle (by viewing different distances from the film centre). A magnification can be defined as d_f/R_f and adjusting the various spacings allows a range of channelling phenomena (and defects which inhibit channelling) to be observed. Fig. 3 shows channelling transmission patterns for 3 different oriented single crystal silicon samples. The width of the bright lines allows the channelling critical angles to be measured. At the time, these patterns had only previously been obtained by expensive high energy particle accelerators.

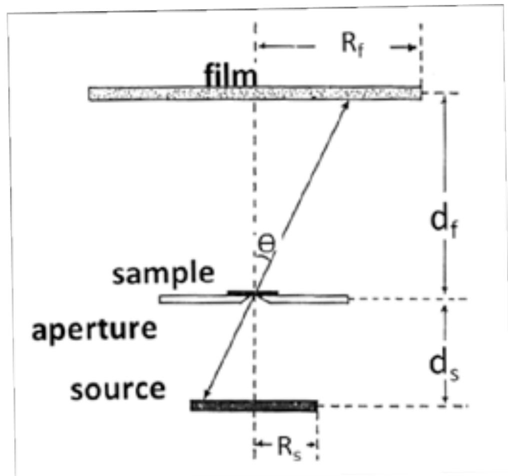

Figure 2: A schematic of the vacuum pinhole camera arrangement whereby α–particles passed through an aperture and sample and impinged onto a cellulose nitrate film. Etching the film revealed the individual α–particle tracks and the channelling directions in the crystal. From Nip and Williams (1972).

Both a conference presentation and a journal paper (Nip and Williams, 1972) were obtained from this work. I presented the paper at a conference in Oslo in 1971 which was very well received. In fact, I was congratulated on the innovative method and had three post-doctoral offers, one of which I accepted at the University of Salford in the UK working with George Carter. Again, this type of innovation was strongly encouraged by Jak: I owe him much for the training in his group that set up my future career in science.

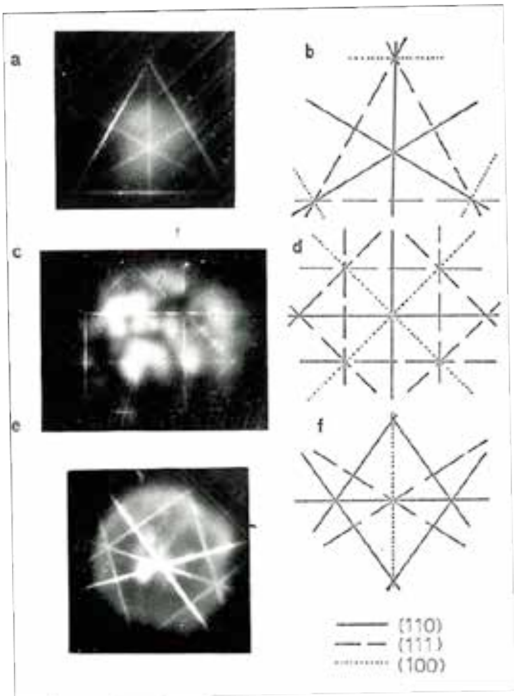

Figure 3: Pinhole channelling patterns from a) <111>, b) <100> and c) <110> oriented silicon thin samples, with the respective stereographic projections in d), e) and f). From Williams (1972).

Very sadly, Hans Nip committed suicide around the time I presented the Norway paper. It was not known by any of our rather close group that Hans was struggling with 'demons' that he could ultimately not overcome. Outwardly he appeared a happy go lucky person, who liked to share jokes and perspectives on life, including his very insightful poems of the week, with his friends and colleagues. Jak was strongly affected by this sad event, chastising himself that he did not detect a problem within such an otherwise caring group of people. For my part, I have become very friendly with Hans's sister Renee and family in the Netherlands. A few years ago she visited Australia and Sydney to see for herself what Hans had described to her as a great country.

Perspectives

Towards the end of my PhD I was married to my wife Ros of over 40 years now. Jak and Irene were at the wedding, as were many of my UNSW colleagues. At events such as this Jak would be excellent value, with an endless number of very witty stories and anecdotes. Years later during my post-doctoral fellowship at the University of Salford in the UK, the Kelly family visited us. They crammed into our very small flat and I can remember that Karina (at about age 14) babysat our two small children while we went out for a meal.

If I look back at where my career has gone, I have a lot to thank Jak for. In my early days in the UK and Denmark, I quickly realised that improvisation and adaptability, the ability to think laterally and problem solving, attributes that I had learnt from Jak, were highly valued by my new colleagues. I was given a problem when I arrived in Salford to measure the range distributions of various ions in materials. I realised that the depth resolution of the Rutherford backscattering method I was using was barely sufficient. It needed to be improved but what to do? After a little thought about how the resolution was improved in the channelling pinhole camera I decided to dramatically change the entrance and exit angle of the analysis beam, calculating a large enhancement in effective depth resolution. It worked better than I imagined. In fact, this simple twist to the Rutherford backscattering technique to improve its depth resolution, a small step learnt quite naturally in working with Jak, helped establish my scientific credibility. It led to collaborative and job opportunities and a very enjoyable life in science. I thank you Jak for giving me the chance to work with you, for what you taught me that not only enriched my career but engendered in me a passion and enthusiasm for science that I have endeavoured to pass on to others.

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Jim Williams

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Professor Williams obtained his BSc (1969) and PhD (1973) degrees from the University of New South Wales before moving to Europe and North America for a series of research and industry appointments, including a member of technical staff at Bell Telephone Laboratories, New Jersey, USA. He returned to Australia to take up an academic post at the Royal Melbourne Institute of Technology in 1978 and became Director of the Microelectronics and Materials Technology Centre in 1982. In 1988 he moved to the Research School of Physical Sciences at ANU as Foundation Professor of the Department of Electronic Materials Engineering. Both of these R&D efforts involved leading large research teams focussed on innovative materials and devices research covering aspects of both fundamental interest and applicability to industry. In 1997 he assumed the additional role of Associate Director of the Research School of Physical Sciences & Engineering at ANU and took up the Directorship of the School in 2002. In 2012 he retired and is now an Emeritus Professor of Electronic Materials Engineering at the ANU.

Professor Williams has carried out research in diverse areas of materials science, nanotechnology, ion-solid interactions and semiconductors for over 40 years. He has published over 450 refereed papers and five books in a broad spectrum of sub-fields within semiconductors, materials science and processing, device fabrication and engineering. His papers are well cited with an h-index of 50 and over 8,000 citations in total. He is particularly well known internationally for his pioneering work on ion implantation into semiconductors, solid phase epitaxial growth of silicon, innovative development of ion beam analysis methods, impurity gettering in silicon and nanoindentation of semiconductors, the latter area leading to prospects for novel patterning of silicon at room temperature. Over the past 20 years he has had an average of 5 invitations per year to deliver keynote plenary or invited papers at major international conferences. He has served on the editorial board of ten international journals and three international conference series. He was awarded the Boas Medal of the Australian Institute of Physics in 1993 and the Thomas Rankin Lyle Medal of the Australian Academy of Science in 2011. He is a Fellow of the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering, the Materials Research Society, American Physical Society, is President of the Australian Materials Research Society and is an IEEE distinguished lecturer. He has served on the MRS Council and has been a Vice President of the International Union of Materials Research Societies. He has been the founding director or initiator of two spin off companies, Acton Semiconductors and WRiota, in 1999 and 2004, respectively.

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Research Cooperation with Past President Jak Kelly

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Abstract

A review of research work done in collaboration with Jak Kelly between 1975 and 2012 at the University of New South Wales requires a rather detailed explanation of the subjects covered. These begin with the pioneering work on very high intensity electron beams of energy range between 10 and 200 keV as well as ion beams and their defect generation in solid material. Combination with lasers led to the whole range of ion generation from few eV to GeV including the need for changing Maxwell's stress tensor of plasma optical properties. This led to the discovery of relativistic self-focusing and subsequently to joint applications based on papers covering solar cells and the reduction of friction in motor engines together with patents. With nuclear energy being 10 million times more efficient than chemical energy there is the possibility that lasers might lower the most dangerous levels of radioactive radiation to the point that it can be neglected.

Introduction

An indication of the importance of my collaboration with Jak Kelly is an obituary we prepared as fellows of the Institute of Physics (London) for its magazine, on Professor Christopher Milner, Head of the School of Physics at the University of New South Wales, and his long years of service (Hora et al. 1998). Milner was highly regarded for establishing the very successful School of Physics and for becoming the only physicist as Dean of Science. No doubt Jak Kelly was very appreciative when Kit Milner offered him an academic position in Sydney following the exciting work he had been doing at the Harwell Research Establishment in England. Jak's new position led to his appointment as professor and later to Head of the School of Physics and Chairman of the Faculty of Science of the UNSW.

Research in physics has numerous instances of adversity that cause friction and hamper progress. Never when working with Jak Kelly did I experience such negativity. If a researcher claimed to have measured velocities faster than c of light in a vacuum, Jak would a priori not take a negative stand and would first look into details for the claim.

Jak's interests followed many directions such as applying his profound knowledge to ion implantation or to defect generation in solids. Other directions were to investigate alternatives for energy generation and to deliberate on nuclear energy. During the times I collaborated with Jak there were many examples of the positive side to research. Although these personal reflections do not include Jak's contributions to areas such as solar-thermal energy production, or luminescence methods for measuring the age of pottery in archaeology, they do include *Electron Beam Treatment of Materials, Low Energy Nuclear Reactions, laser interaction with plasmas, and Nuclear Energy without Problems of Radioactive Radiation* that I have covered below.

Jak's positive attitude emerged at times when organisational decisions had to be made. For example the University of New South Wales was offered the purchase of the van-de-Graaf accelerator from the Australian National University when it purchased a new accelerator. It took Jak less than a second to accept the offer although there had to be a lot of work done before rich fruits of his decision could be harvested.

The following is a summary of results of our collaborative research. They reflect Jak's exceptional ingenuity and attitude to solving problems and even though not all problems were solved, in most cases the research helped to open new doors to knowledge.

Electron Beam Treatment of Materials

Electron beams could be seen long before the year 1900 in the electric discharges within low pressure Geißler tubes before one knew what an electron is. Using electron beams became more common in Braun's television tubes and by the wave properties in electron microscopes from about 1930. But to get the electron beams at such high intensities that these could melt materials, cut or weld them, came along only just around 1950. Jak Kelly's first publication was in Nature (Bruce et al. 1951) from work in Sydney about wave properties, and when he joined the University of Reading in England for his Ph.D. project, this was the place where the very intense electron beams were used. Metals with the highest melting temperatures above about 2000 centigrade could be heated up and liquid droplets could be studied. Kelly's paper (1959) described the "Electron bombardment apparatus for vacuum evaporation" leading to the first possibility to measure the surface tension of these materials (Tille et al. 1963) as basis of surface potential measurements (Townsend et al. 1967). On top it was highly important to study the crystal defects in materials by this bombardment of the electrons and also by beams of intense ions of similar high energies and current densities. About the crystal defects, a standard book was published by Kelly (Townsend et al. 1976, cited 350 times) and he became a leading authority in this field of high importance for material research when he was leading international conference.

Similar but independent studies with high intensity electron beams came from another side for cutting and welding of metals under extreme conditions in Germany (Steigerwald 1961; Hora 1961). It was even possible that the basically fixed optical fundamental absorption of silicon could be changed (Hora 1961a). On top it could be shown that the very intense electron beams could produce defects in silicon for changing n-conducting crystals into p-conducting states producing diodes (Hora 1962) for later use for transistors at electron energies of 50 keV, while the established value by Lark-Horowitz from simplified crystal theory needed more than 200 keV. Another result with homogeneous semiconductors (GaAs) led to the calculation of the laser threshold at pumping with electron beams predicted (Hora 1964) exactly in agreement with subsequent measurements (Hora 1965a; 1965b; 1965c).

When I accepted the offer of the Foundation Chair in Theoretical Physics at the University of new South Wales in Sydney/Australia in 1975, I brought in this background for cooperation with Jak Kelly, though my appointment was based on my achievements of purely theoretical results. These were the clarification of the

Richardson equations for electron emission where the analysis on the basis of an integral equation led to the general spectral response theory of photoelectric electron emission (Görlich et al. 1957; 1957a; 1958) with the result that the general response function is given by a volume process in contrast to the established theory of the surface effect (Herbert Fröhlich; Igor Tamm). This was clarifying the unique property of the Cs_3Sb photocathode, discovered by Görlich 1936. This and similar compounds substituted soon all earlier emitters of photocells with the instabilities and low efficiencies. As another mathematical achievement, I had discovered the mechanical forces in plasmas by irradiation of light, if the correct dielectric optical properties were used (Hora et al. 1967) leading then to the exact modification of Maxwell's stress tensor in plasmas (Hora 1969). I solved the two coupled nonlinear differential equations for the complete relativistic motion of electrons in laser fields (Hora 1973) permitting the general solution of relativistic laser beams for self focusing in plasmas (Hora 1975).

This research background was well harmonizing with the interests of Jak Kelly though I was mostly involved with establishing lectures in higher mechanics, electrodynamics based on Maxwell's theory and the mathematical foundation for solving the Schrödinger and the Dirac equation for undergraduates, where I profited especially on my mathematical and theoretical education from German universities.

The sub-threshold energies of electrons for producing n- into p-conducting silicon was the first joint project to be studied with Jak Kelly, especially after I just got granted a patent (Hora 1977) how to produce solar cells by much lower costs and avoiding aggressive and poisonous chemicals. I had to win with a patent process against the AEG in Germany. This work was the topic of a Honour's thesis of Hinckley et al. (1979; 1980) supervised together with Kelly where the student received a first class honours and the University Medal.

Using the direction of crystal defect generation by ion implantation in silicon – pioneered by Kelly (Townsend et al. 1976) – I spend a study semester with the Siemens research laboratory in Munich-Perlach (Hora 1983) which results were then further studied at UNSW in cooperation with Julian Goldsmid and with using laser annealing by George Paul (Goldsmid et al. 1984) in cooperation with E.F. Krimmel (Siemens Research Munich-Perlach) about laser measurement of thermal conductivity. It should be mentioned that Goldsmid's work led to a widely used instrument for identifying diamond crystals.

For the ion implantation, it was interesting to use laser irradiated targets as sources about which I had experience from the laser-plasma interaction. In cooperation with Jak Kelly, J. Len Hughes from the Australian National University et al. we got granted a US-Patent (Kelly et al. 1980; 1981). This was then used for studies how to reduce the friction of iron after intensive and high energy implantation of tin ions. These studies were performed after I had become Emeritus Professor at the UNSW and had a Konrad-Zuse-Professorship in the Faculty of Electrical Engineering in Regensburg, Germany. These results (Boody et al. 1996) received more than 100 citations and through my contacts from the Rotary Club with the Regensburg plant of BMW, our research found interest by the R&D Chief, Dr.-Ing. Wolfgang Reitzle (BMW, Munich). The tin implantation reduced the friction in steel by a factor up to ten which result was measured by Savage (1984) at the University of Wollongong in contact with Jak Kelly. It was considered to improve motor engines for racing cars. The unique measurement by Savage (1984) led to the result, that when the iron surface was scratched off by friction under long use, the implanted tin ions are moving to the inner volume of the iron. We had no further information whether the interest was stopped when BMW withdraw from car racing or due to the fact that Reitzle had changed to become the CEO of Jaguar in England.

The production of very low cost solar cells with electron beam generated p-n junction was reported (Ghoranneviss et al. 2006) and an efficiency of about 10% at not optimized parameters was measured. This may open the production of solar cells in plastic foils of organic materials for an economic contribution to solar energy. The commercial level of present silicon solar cells is mostly determined by the high equipment and connections costs to be added to the present comparably high costs of the silicon cells. Kelly as the Editor-in-Chief of the Journal and Proceedings of the Royal Society of New South Wales during this time was interested and involved in reports and publications of related topics (Osman et al. 2007).

Low Energy Nuclear Reactions

This topic needs some introduction and explanation because this is related to the widely criticized "cold fusion". More than 95% of all what has been published since 1989 is unacceptable for physicists and it is important to select the few facts which may be taken seriously. The whole development came from a very important line of research, from the muon-catalysed fusion (Jones 1986; Rafelski et al. 1987). Along these lines of research, the incorporation of very large densities of deuterium in palladium resulted in the measured emission of neutrons (Jones et al. 1989). The confusion about these facts resulted from a press conference of Fleischmann and Pons on 23 March 1989 at Bingham Young University in Utah (Miley, see Hora 2011).

Jak Kelly's attention to these developments followed the results of Jones et al. (1989) by being involved from the early stages (Hora et al. 2001; Miley et al. 2009). Following the serious line of Jones and Rafelski, interesting physics approaches by Parmenter and Lamb jr. analysed Debye-length influences by the Thomas-Fermi-Mott model including the Oppeneheimer-Phillips process (Parmenter et al. 1989; 1990) and it may not have been a coincidence, that the evaluation of Coulomb screening was a key point of the work with Jak Kelly (Hora et al. 1993) which was later confirmed by ab initio quantum mechanics by Czerski et al. (2001) and Huke et al. (2008).

The present situation was summarized by a media source (Krivit 2013) in the following way: "The older researchers who have fought the battle for 'cold fusion' for 24 years have, sadly, found themselves with increasingly less funding, research, and mainstream media coverage. Their conference papers, for the most part, repeat the research they have done for many years. In some cases, they have presented the same experiments for a decade. During this time, they have made little progress, both in the expansion of scientific knowledge and toward commercialization of LENR technologies. On the other hand, something fascinating is taking place. As a result of slow but steady mainstream acceptance of LENR (by Royal Dutch Shell, Toyota Motor Corp., CERN, ANS, Boeing, ST Microelectronics, Elsevier, and Wiley and Sons), mainstream science and industry are taking notice."

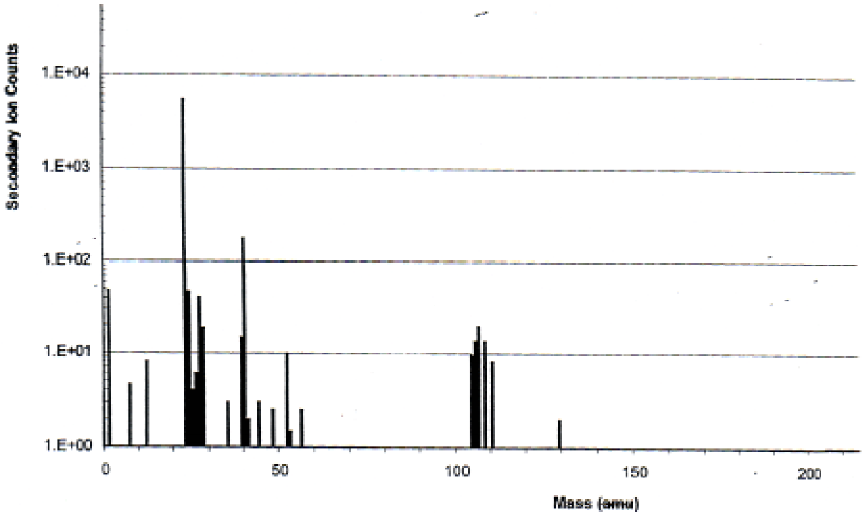

Figure 1a. Abundance of elements in palladium before loading with deuterium (Miley et al. 1996).

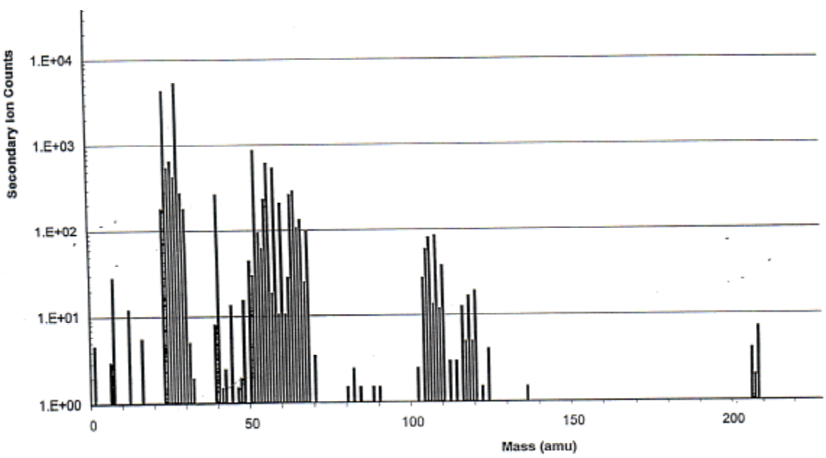

Figure 1b. The elements detected in palladium after electrolytic loading of deuterium.

In this situation it is necessary to give more detailed explanation to a rather complicate but completely solid basis for confirming the nuclear reaction mechanism when high densities of deuterium are incorporated in palladium or in comparable metals as nickel etc. before talking about the results established with Jak Kelly (Hora et al. 1993). The solid basis of the phenomena was given by Miley's et al. (1996) unique measurement of a Maruhn-Greiner Maximum (Hora et al. 2007). This can be mentioned as a well elaborated proof of the generation of nuclei from the whole list of stable nuclei up to lead, Figs. 1a and 1b. This discovery by Miley et al. (1996) has been documented as a "Low Energy Nuclear Reaction" LENR process. The distribution of the generation probability of the generated nuclei G(Z) on the nucleon proton number as discovered by Miley (1996), Fig. 2, which is similar to SAD (standard abundance distribution of elements in the universe, Rauscher et al. 1994; Hora et al. 1998) with a relation to the nuclear magic numbers (Hora 1998).

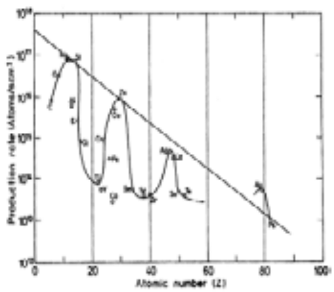

Figure 2. Generation probability G(Z) of elements with proton number Z after the reaction of the deuterium in the palladium (Miley et al. 1996, 2002).

When listing the distribution G(A) depending on the nucleon number A the minimum for A between 125 and 175, Fig. 3, this has a similarity to the distribution G(A) for the fission of uranium shown in Fig. 4. For Uranium 236 there is a large-scale minimum at A=118, just the half nucleon number of the Uranium nucleus (Feltus 2002). The splitting of Uranium nuclei is there from an unexcited state. However, if the heavy nucleus has been excited to energies around MeV, a local maximum appears for uranium as a local peak (Fig. 5 at A = 118) as it was theoretically explained by Maruhn et al. (1974).

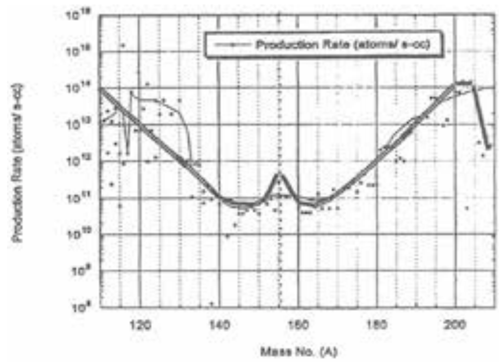

Figure 3. Measurement of Low Energy Nuclear Reactions (LENR) resulting in the distribution G(A) of the generation probability of nuclei of nucleon number A for the range between 125 and 185. Detailed nuclear mass spectrum of the LENR generation probability at the highest A-minimum with a local (Maruhn-Greiner) maximum at A = 155.

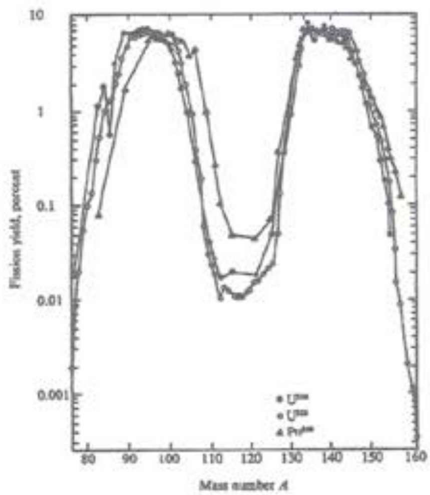

Figure 4. Distribution G(A) of the generation probability of nuclei of nucleon number A as measured from the nuclear fission of ^{233}U, ^{235}U and ^{239}Pu (Feltus 2002).

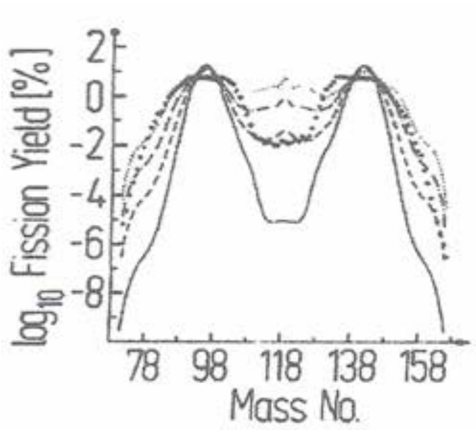

Figure 5. Fission mass distribution curves for ^{236}U calculated when the nucleus, at the time of fission, is excited to a temperature 0, 0.5, 1, and 7 MeV (upward sequence of Ref. Maruhn et al. 1974).

It is important to note for the case of deuterium in palladium, that a similar local maximum peak was seen in the measurement of the distribution G(A). At LENR (Miley et al. 1996) is a similar large-scale minimum at A = 155, Fig. 3 and *also a local maximum as a peak similar to the case of uranium fission of Fig. 5.* This fact of the observed Maruhn-Greiner Maximum (Maruhn et al. 1974) corresponds to a compound nuclear fission reaction (Hora et al. 1997; 1998a; 1998b; 1999; 1999a; 2000a; 2001) through a nucleus $^{310}X_{126}$ with Z = 126 protons and 310 – 126 = 184 neutrons. Both numbers 126 and 184 are magic nuclear numbers (Hora et al. 2001) and it is significant, that the evaluations of super heavy nuclei with Z between 116 and 120 have both numbers for well pronounced energy minima at 126 and 184 (Kuzmina et al. 2012).

Before Miley's discovery of the LENR process and how this was ascertained by the Maruhn-Greiner maximum, an important step was that with Kelly about the evaluation of *the plasma screening process for deuterons in palladium* crystals (see Fig. 1 in Hora et al. 1993) where the numbers for the reaction probabilities of Rafelski (see Jones et al. 1989) were completely fitting with a deuterium reaction in 2 pm distance. Different to most of the experiments with electrolytes, the measurements by Prelas et al. (1990) were loading palladium with deuterium in the gas phase or by plasma mechanisms. This permitted an evaluation by assuming that the deuterons in the palladium crystal were behaving like a Maxwellian gas and the theory of screening of Coulomb repulsion could be described in the same way as in the theory of Ichimaru (1994) for high temperature plasmas. In his case the Coulomb repulsion arrived at a reduction factor of 5. In our case (Hora et al. 1993) the screening has a factor of 13 according to the evaluation of experiments of Prelas et al. (1990). The Maxwellian deuterium ions are then, for distances down to 2 pm, behaving similarly to neutral particles. This agrees then to a reaction probability similar to the well-known inverse K-electron capture radioactivity. This reasonable property allowed considering that the deuterons can stick together at 2 pm distance as a Bose-Einstein cluster within which no locality of the deuterons is possible (Hora et al. 2007). The 10 pm diameter cluster reacts then with a palladium nucleus via a compound nucleus $^{310}X_{126}$ to fit with the measured Maruhn-Greiner local maximum. This result is based on the evaluation of the results of Rafelski (1987) and Jones et al. (1989) where Fig. 1 of Hora (1983) shows the reaction probabilities of Rafelski on which basis Kelly could evaluate reactions for D-D in 2 pm distance.

The phenomenologically derived screening by the factor 13 derived with Kelly in 1993 (Hora et al. 1993; 1996; 1998a) was confirmed from a complete quantum mechanical derivation (Czerski et al. (2001); Huke et al. (2008)). The long time uncertain question whether the LENR reactions emit neutrons of more than MeV energy from nuclear reactions was measured with recently developed diamond detectors (Prelas et al. 2012) resulting in a neutron emission of considerably more than one million within five minutes. These results led to the recent activities in industry laboratories for clarification of the mechanisms with the potential of far ranging applications.

Brian Josephson was interested in the physics of LENR and visited the UNSW 2005 after he had several times discussed these activities at the Nobel-Laureate meetings in Lindau/Germany. Attention was given by the team with Jak Kelly (Osman et al. 2005; Hora et al. 2005). He was at this time President of the Royal Society of New South Wales and arranged the then scheduled Pollock Lecture to be presented by Nobel Laureate Josephson and celebrated as a highly visited event.

Kelly's involvement in laser interaction with plasmas

Jak Kelly had joined the research team of laser interactions, including relativistic conditions and ion acceleration mechanisms, described in granted patents (Kelly et al. 1980; 1981) that were assigned to UNISEARCH, the commercialisation branch of the UNSW. This resulted in the first derivation of electric double layers in plasmas (Hora et al. 1984) and surface tension (Hora et al. (1989). The theory of relativistic self- focusing of laser beams in plasmas (Hora 1975) was the starting point for a number of studies. A further point of joint interest arrived about the topic of laser driven ion sources about which Jak was well familiar through his van-de-Graaf accelerator after it was successfully working. I had for more than one year a position as Attache Remuneree at the CERN Laboratory in Geneva/Switzerland with the aim, what can be done that the ion sources of accelerators may be improved by using lasers (Haseroth et al. 1993, 1996; Hora et al. 1992). Pioneering experiments were done before at the Russian high-energy physics research centre in Dubna well following the general developments on the main stream of laser-plasma interaction. This is the reason why it is necessary to summarise the related research in the following.

During my time at CERN, I was in close contact with Jak who had prepared laser work at his accelerator in combination to study the problems of laser driven ion sources. He had also prepared PhD students to contribute to this problem in cooperation with CERN, well following the concept of the earlier granted patents to UNISEARCH (Kelly et al. 1980, 1981). After successful experiments at CERN by a very experienced Postdoc from Munich (Hora et al. 1992) the later work by Russian colleagues did not lead at the expected results.

This research work on laser interaction with plasmas for ion generation is needed in the following to explain the development of ultrahigh acceleration of plasma blocks and of ultrahigh ion currents generated by nonlinear effects. The ultrahigh acceleration of macroscopic objects by more than 10^{20} cm/s^2 was the result of theory and computations at the UNSW (Hora et al. 1979a; Hora 1981) and was first measured by Sauerbrey (1996) who underlined that these acceleration were 100,000 times higher than ever produced in a laboratory before. The generated space charge neutralized ion macroscopic blocks had ion current densities above 10^{12} Amps/cm^2 (Hora et al. 2002) that were much higher than a million times than produced in classical accelerators. All these developments were considered in some contact with Jak Kelly leading then to his aspects (Hora et al. 2009) of a new scheme of laser driven nuclear fusion where the very dangerous radiation problems of radioactivity may be eliminated.

After these results with very energetic ion acceleration for all kinds of applications, it is necessary to differentiate against the basically different ultrahigh acceleration of plasma blocks by avoiding relativistic self-focusing. These are becoming important also for the application on laser driven fusion energy and are to be developed now for hadron therapy of cancers and other applications. This type of acceleration goes back to the early cooperation of the team including Jak Kelly as shown by his co-authorship for a scientific magazine (Hora et al. 2009) where theoretical-numerical predictions of 1977 from the UNSW (Hora 1991), however, needed a long time before the experimental verification was reached by Sauerbrey (1996). This was possible only after the radical new discovery (Strickland et al. 1986) of CPA (Chirped Pulse Amplification) permitted the generation of laser pulses with less than picosecond (ps) duration (down to attoseconds, Krausz et al. 2009) and with powers above petawatt (PW) (Mourou et al. 2006).

The developments go back to the effect discovered by Linlor (1963) of the crucial difference between thermal-chaotic hydrodynamic processes and the contrary basic nonlinearity determined mechanisms just opened by the laser leading to collective effects (Hora 2013). This touches the fundamental problems expressed by Edward Teller and are going to become under control by damping and stabilization of complex systems by Lord Robert May of Oxford (2011) following his Dirac Lecture in May 2011 which was supported by the RSNSW. For the stabilization mechanisms see the discussion about Edward Teller and Lord May in a recollection of Hora (2011). Before Linlor's discovery, laser pulses up to MW power when hitting targets in vacuum heated these up to plasmas of about 20,000 centigrade by classical thermokinetic pressures and fluid-dynamics, seen e.g., from the emission of ions of the corresponding energies if few eV. When Linlor applied very smoothly produced laser pulses of about 10ns duration by Q-switch techniques, the measured ion energies jumped from few eV to several thousand eV by changing the laser power by a factor of about fife only. The hope that then the laser driven thermonuclear fusion energy generation, however, could not be fulfilled, because the keV ions were not thermal but were linearly increasing on the charge number Z. Thermal processes would results in ions of same energy. The Z-dependence of the energy indicated an electrodynamic acceleration process, different from thermal action.

The action of electrodynamic forces goes back to the discovery by William Thomson (Lord Kelvin) who in 1845 discovered, that an electrical charge-free medium can be accelerated by divergent electrostatic fields. After discovery of Maxwell's equations, this ponderomotive force appeared also beyond electrostatics in time dependent electromagnetic fields, discovered by Weibel (1958) when electrons in vacuum could be confined within the nodes of standing waves of microwaves, and later by laser fields. The same could be concluded for space-charge neutral plasmas – similar to Kelvin's uncharged dielectric materials. The new situation for plasmas is due to the gradients of the optical dielectric and absorption constants (Hora et al. 1967) which were then just derived. The optical constants could be used for describing spatial variations of inhomogeneous dielectric plasma properties. This can be seen when a laser pulse penetrates a slab of plasma (Fig. 6) where the negative gradient of the optical constant results in forces moving the plasmas towards lower density.

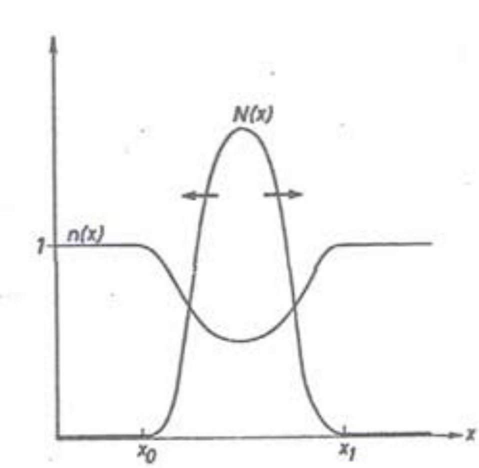

Fig. 6. Plasma layer between depths x_0 and x_1 with electron density N(x) and optical refractive index n(x). The negative gradient of n causes nonlinear (ponderomotive) forces (arrows) in the space charge neutral plasma (Hora et al. 1967).

The force density **f** in a plasma is given by the classical thermal gas-dynamic pressure $p=3n_pkT/2$ where n_p is particle density, k is Boltzmann's constant and T the temperature, and given by the nonlinear force $\mathbf{f}_{NL}$ due to electro-dynamic interaction

$$\mathbf{f} = -\nabla p + \mathbf{f}_N \qquad (1)$$

The nonlinear (optical corrected) nonlinear force was derived from Maxwell's stress tensor with the optical refractive index **n** for the stationary conditions from momentum conservation (Hora 1969) and for the general transient case with the unity tensor **1** and the electric **E** and magnetic field **H** of the laser:

$$\mathbf{f}_{NL} = \nabla\bullet[\mathbf{EE} + \mathbf{HH} - 0.5(\mathbf{E}^2 + \mathbf{H}^2)\mathbf{1} + (1+(\partial/\partial t)/\omega)(\mathbf{n}^2-1)\mathbf{EE}]/(4\pi) - (\partial/\partial t)\mathbf{E} \times \mathbf{H}/(4\pi c) \qquad (2)$$

from symmetry results (Hora 1985) for the final equation of motion (1) being Lorentz and gauge invariant (Rowlands 1990).

For simplified geometry with plane wave laser interaction, Eq. (2) can be reduced to

$$\mathbf{f}_{NL} = -(\partial/\partial x)(\mathbf{E}^2+\mathbf{H}^2)/(8\pi)$$
$$= -(\omega_p/\omega)^2(\partial/\partial x)(\mathbf{E}_v^2/\mathbf{n})/(16\pi) \qquad (3)$$

For high accuracy evaluations following the nonlinearity principle (Hora 2000) all components of the stress tensor need to be included (Cicchitelli et al. 1990). The first expression is the basic relation with the gradient of the electromagnetic energy density and the second expression is formally related to Kelvin's ponderomotive force, which was derived for electrostatics without magnetic fields and not for plasma properties. Following Eq. (2), the nonlinear force dominates over the thermal pressure, when the non-relativistic oscillation (quiver) energy of the electrons in the laser field exceeds the thermal energy

$$\varepsilon_{osc} = \mathbf{E}^2/(8\pi n_{ec}) > (3/2)n_e kT \qquad (4)$$

where **E** is the electric laser field and n_{ec} is the critical electron density n_e using the real part of the refractive index in the plasma $\mathbf{n} = (1 - \omega^2/\omega_p^2)^{1/2}$ which is zero when the laser radian frequency ω is equal to the plasma frequency $\omega_p = (4\pi n_e e^2/m)^{1/2}$ with the charge e and mass m of the electron.

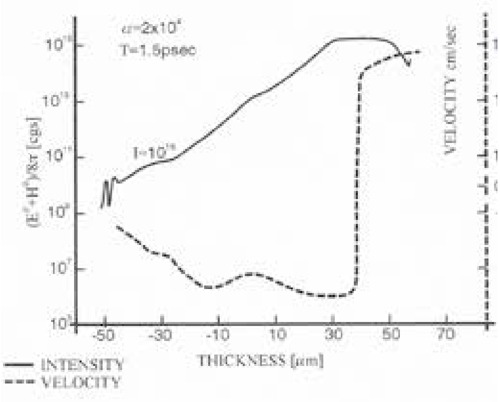

Fig. 7. 10^{18} W/cm² neodymium laser incident from the right hand side on an initially 100 eV hot very low reflecting bi-Rayleigh deuterium plasma profile, showing after 1.5ps interaction the electromagnetic energy density (Eq. 3). The dynamic development had accelerated the plasma block of 20 vacuum wave length thickness moving against the laser with velocities above 10^9 cm/s² and another into the plasma (combining results from p. 178 & 179 of Ref. Hora (1981)) with > 10^{20}cm/s² ultrahigh acceleration.

Using a general fluid-dynamic plasma-code with collisions, thermal equipartition between electron and ion temperature and with pressures with inclusion of the nonlinear force, the numerical result of Fig. 7 was achieved (Hora et al. 1979a; Hora 1981, p. 179) showing an acceleration of more than 10^{20} cm/s² of deuterium plasma against the laser light. In 1980, ps laser pulses with the high intensity were by far not available. But there was another reason that any experimental proof was impossible. The computations were performed with ideal plane geometry of the plasma target at plane wave laser incidence. Just at the time of the computations, the relativistic self-focusing was discovered (Hora 1975) such that any laser prepulse produced a plasma plume which squeezed the intense laser pulse to less than wave length diameter by relativistic self-focusing with subsequent very high ion acceleration into all directions (Basov et al. 1986; Häuser et al. 1988).

The situation changed drastically after the discovery of CPA (Strickland et al. 1986) when ps and shorter laser pulses above TW (Mourou et al. 2006) or 2 PW power (Cowan et al. 1999) were available. For technical reasons to produce the pulses without pre-pulses, their suppression by a very high contrast ratio was necessary to avoid the plasma plume. This led to the measurement of some strange plasma acceleration (Kalashinkov et al. 1994). A very convincing clarification by Sauerbrey (1996) was the measurement with similar pulses from very high quality KrF laser of 10^{18} W/cm² laser intensity, where the Doppler effect for the plasma front moving against the laser beam perpendicular to the target surface showed an acceleration of 2×10^{20} cm/s². This was in the range of the similar computer results with accelerations of Fig. 6 (Hora 1981), the more detailed evaluations (Hora et al. 2007a) were exactly reproducing the measurement of Sauerbrey if a dielectric swelling of the laser field of a factor 3 could be concluded, very similar to the comparable results by Badziak et al. (1999). The role of eliminating the pre-pulse was measured in a splendid way by Zhang et al. (1998) from the fact that the usually observed very high intensity hard x-rays at relativistic self-focusing were absent when using extremely high contrast. But if a ps pre-pulse was irradiated 70 ps before the main pulse, the x-rays were same as usual. The 70ps were calculated for the time to produce the plume. The repetition of the Doppler-effect measurement by Sauerbrey needed extremely sophisticated techniques and succeeded by Földes et al. (2000).

Sauerbrey (1996) underlined in the summary of his paper in order not to be missed, that his measurement of the nonlinear force driven plasma block – as theoretically-numerically expected since 1978 – was 100,000 times higher than any acceleration measured before in a laboratory. On top of the ultrahigh acceleration, a further result was (Hora et al. 2002) that the space-charge neutral plasma block consisted in an ultrahigh ion current density, more than million times higher than any accelerator could produce. This plasma block had the origin in the dielectrically strongly increased skin depth of the interaction by the nonlinear force. Its highly directed motion was in contrast to the ion acceleration by relativistic self-focusing which is going into all directions (Basov et al. 1986; Häuser et al. 1988). The directivity of the plasma blocks was experimentally confirmed as well as the plasma block behind the critical density (see Fig. 6) moving into the laser pulse direction (Badziak et al. 2004; Badziak et al. 2004a).

This overview of the general physical development of laser plasma interaction – as topic of discussions with Jak Kelly – explains not only how the points of applications had been developed, beginning with the work of radiation interaction (Hinckley et al. 1979, 1980) or the generation of energetic ions (Kelly et al. 1979; 1980) by laser interaction with targets, or the continuation for using as laser driven ion sources of accelerators at CERN (Haseroth et al. 1993; 1995). This was the topic of the discussions about the worldwide large-scale developments how lasers can lead to solve the problem of alternative energy generation without polluting the atmosphere with carbon dioxide CO_2. After long years developments, the just described discovery of the ultrahigh acceleration of plasma blocks led to an alternative method which was summarized in cooperation with Jak Kelly in a general article in a physics magazine (Hora et al. 2009), are summarized in the following section with an update for the recent developments.

Prospects of Nuclear Energy without Problems of Radioactive Radiation

The result of the ultrahigh acceleration of plasma blocks offered the possibility for a basically new scheme of generating low cost, unlimited, safe nuclear fusion energy and without the problems of generating most dangerous nuclear radiation as summarized by Jak Kelly (Hora et al. 2009). This was explained in more details in due course (Hora 2009; Hora et al. 2010; Miley et al. 2011) and follows the attempt to use the 10 million times more efficient nuclear energy production than available by chemical energy e.g., by burning coal, however with the goal that the emission of radioactive radiation including neutron generation per gained energy has to be of a lower value than from burning coal. This goal of ignoring the problem of dangerous radioactive radiation can be ignored, when burning protons with the boron isotope 11 (HB11) as fusion fuel in contrast to the usual fusion fuel of heavy and superheavy deuterium D and tritium T (DT).

In view that the emission of carbon dioxide into the atmosphere should be reduced by more than 80% of the present value, the need for alternative energy sources is of highest priority. Nuclear energy from the presently developed fission reactors is at present the second largest energy source while the managing of the radiation especially of the waste from the reactors and safety against unexpected incidents is solved to a very high degree but just not at a total 100% solution. On the other hand, energy from nuclear reaction processes is extremely interesting because the gained energy is more than 10 million times higher compared from exothermal chemical reactions. Despite an enormous amount of research, the aim of a fusion power station with controlled generated nuclear fusion is not yet at the level of break-even, even not yet for a power station with the easiest fusion of (DT).

The most advanced DT fusion process is that with nanosecond lasers pulses. If the lasers are heating and compressing the fuel to densities about 1000 times of the solid state, the thermal based process involves numerous losses and difficulties. The laser energy conversion into electrons is delayed by the collisions; then the thermal energy of the electrons has to be transferred by delaying equipartition processes into ion energy whose pressure is then determining the plasma dynamics. Instabilities and radiation losses are unavoidable (Hora et al. 1998c, 1998d). Nevertheless, the extension of all experiments with direct laser driving and adiabatic volume ignition led to the highest fusion gains (Hora 2013) and the extension of the results to nanosecond laser energy inputs of few megajoule from the largest laser on earth (Moses et al. 2008; Lindl et al. 2011; Haan et al. 2011) indicated that breakeven may be reached where the main advantage is the self-heat by the generated alpha particles and some self absorption of bremsstrahlung resulting in a jump of the volume ignition (Hora et al. 1978; 1998). The most studied indirect drive spark ignition has still nearly 1000 times too low gains (Hora 2013) and the self-heat is aimed for a solution. But even if this would be solved and one would consider the completely harmless final reaction products, the intermediary large amounts of neutrons, decaying with a half life of 12 minutes into stable end-products (electrons and water) have the problem of handling the tritium in the reactor and what during the 12 minutes life time is happening producing radioactive nuclei in the environment (Tahir et al. 1999).

A dream reaction is known from the beginning from the reaction of protons with the boron-11 isotope as being absolute clean. For the performance of laser driven fusion by the mentioned thermal processes by nanosecond laser pulses, compression to 100,000 times solids is necessary and all together this is about 100,000 times more difficult than the just not yet achieved thermal reaction with ns laser pulses.

The conditions are changing as it was shown at least from several computations with about same results from different approaches. With the advent of the nonlinear force driven ultrahigh acceleration of plasma blocks using ps laser pulses of PW power, the side-on ignition of a fusion flame in solid density fuel is possible now after the development of the CPA technique (Strickland et al. 1986; Mourou et al. 2006). The side-on ignition was the study by Chu (1972) and Bobin (1974) where a laser pulse irradiating solid density DT is leading to ignite a fusion flame. The computations of Chu resulted in the need of a minimum energy flux of 4×10^8 J/cm^2. This condition was far above the possibilities in 1972 and laser driven fusion energy followed the thermal compression and ignition of DT by nanosecond laser pulses (Moses et al. 2006; Lindl et al. 2011;

Haan et al. 2011). The conditions of breakeven can well be reached by direct drive volume ignition (Hora 2013) with 2 MJ nanosecond laser pulses due to a jump in gain by the self-absorption of alphas particles and by partial re-absorption of bremsstrahlung. This may now be a way also for indirect drive spark ignition (Haan et al. 2011).

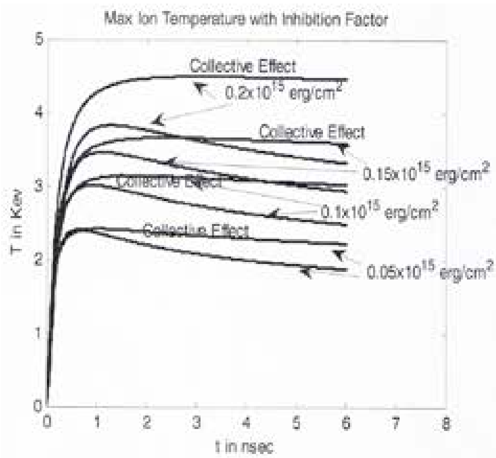

Figure 8. Dependence of DT plasma temperature T on time t after igniting by a ps deposition energy flux E given as the parameter to produce a fusion flame, generalizing the computations of Chu (1972) by using the collective effect for the alpha particle stopping and the inhibition factor for varying parameter of input energy flux density E*. Ignition is reached only above such E* where the temperature T does not decay on time t (Hora et al. 2008)*

An improvement of the flame ignition following Chu (1972) with updating of later discovered phenomena (Hora et al. 2008) (Fig. 8), arrived at the improved threshold for ignition of solid density DT-fusion of

$$E^* > 2\times10^7 \text{ J/cm}^2 \qquad (5).$$

The result of the ultrahigh acceleration of plasma blocks (Hora 1981) when using CPA generated ps high intensity laser pulses (Sauerbrey 1996) led to the possibility (Hora 2009) to ignite solid density DT with laser energy fluxes above petawatt/cm^2, calculated for plane geometry (about other geometries, see below).

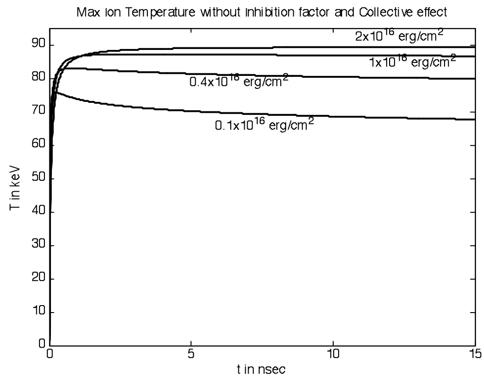

Figure 9. Temperature dependence on time t of the fusion flames for p-^{11}B (HB11) under the same assumptions of Chu (1972) for comparison with DT fusion. The 20-times reduction of E (Hora et al. 2008) is not included and the alpha stopping is as in the DT case only by electrons (Hora et al. 2009). The ion stopping with an avalanche of secondary production of alpha particles will lead to a much higher fusion gain for HB11 (Hora 2012).*

When the positive result for DT was applied to compute the case of HB11, it was rather surprising, Fig. 9, that the threshold for the side-on ignition was only 5 to 10 times more difficult than for DT (and not 100,000 times) (Hora 2009, Hora et al. 2009, 2010; Li 2010; Miley et al. 2011). On top, these computations were based on the Gabor collective alpha-stopping powers with electrons only as in the case of DT. The fusion gains will be dramatically increased if the alpha stoping includes the secondary ion interactions, where the resulting alpha particles all had the same energy of 2.88 MeV. When these alphas are colliding with boron nuclei, central collisions transfer 630 keV energy. This energy is in the wide range of an exceptional very large reaction cross section leading to a second boron reaction with a proton nucleus to produce three new alphas.

This multiplying avalanche reaction of the alphas can produce a gain very much higher than the gain from DT with the possibility to lead to an ideal burning of the fuel until exhaustion, depending of the detailed plasma fluid dynamics of the fuel after the ps-laser-pulse initiation of the fusion flame. The only bottleneck is the ignition by a laser fusion energy flux density of which at present it can be assumed that this is in the range of that for DT, Eq. (5), because this is a 2-dimensional process while the avalanche process is 3-dimensional.

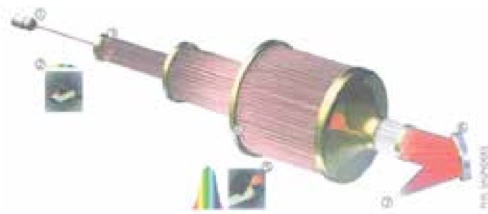

Figure 10. For a new design ICAN (Mourou et al. 2013) of a CPA laser for pulses shorter than 1 ps and with powers of Petawatt to Exawatt and higher, the use of fibres is being designed with an initial partial section for demonstration of highest quality laser pulses on comparably low costs. The beam output of the fibre bundle irradiating a focusing mirror 6 has diffraction limited quality for focusing to highest intensities. It is expected (Mourou 2013) that a cross section of 100 cm² ps laser beam may be produced with kJ energy pulse corresponding to a Petawatt power.

The comparison between DT and HB11 for plane geometry and without the alpha-avalanche was only a first step of the computations (Hora 2009, Hora et al. 2009). What has not been included is that in the case of a fusion power station, only a (comparably large) section of plane geometry can be used for the interaction. A cylindrical section will suffer from lateral losses of energy and particles. One possibility to overcome this is to confine the cylindrical reaction by very large cylindrical magnetic fields (Moustaizis et al. 2003) after the shock processes in the fuel got under control in details from general plasma-hydrodynamics (Lalousis et al. 2013). This may be possible with the now available cylindrical magnetic fields above 10 kilotesla (Fujioka et al. 2013). Another way is to change from plane into spherical irradiation fronts (Hora et al. 2012; Moustaizis et al. 2013). In this case, however, ps laser pulses with a power above 100 PW are needed. 2 PW were achieved in 1999 (Cowan et al. 1999) and the level of 7 PW was reached in 2013. After the new scheme with fibre-optics accelerators ICAN (Mourou et al. 2013) in Fig. 10 can produce PW highest quality laser pulses at a cross section of 100 cm^2, a spherical irradiation of one meter radius may produce more than 900 PW laser pulses of 1 ps duration spherically propagating to extreme high intensities, see Fig. 11.

The conditions for initiating a spherical HB11 reaction depend on the result of Eq. (5) where a possibility may be to work with lower energy flux densities due to a small degree of avalanche alpha processes. The chance for this reduction, however, may be rather limited, because the initiation process in the ps range may be too short. The following evaluations are realistically based on the limit of Eq. (5) needing the operation with Exawatt laser pulses, though the total reaction efficiencies can be considerably much better than for DT. First evaluations resulted in gains of about 80 when generating 100 MJ fusion energy that up to 95% of which electrostatic conversion into electric power may be used. GW power stations may operate with less than about 15

Hz sequence of shots. The main advantage of working with sub-ps laser pulses consists in the collective conversion (Hora 2013a) of laser energy into macroscopic motion of the plasma blocks nearly without thermal losses in contrast to the spherical thermal compression and ignition of DT plasma being close to break-even (Hora 2013, Hora et al. 2013).

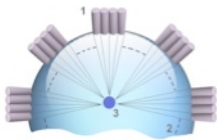

Figure 11. Combining the fibre output of an ICAN laser (Fig. 10) to a sphere (1) of more than 1m radius may produce a converging spherical laser pulse of 1ps duration and Exawatt power for interaction on a sphere 3 in the centre. Apart from diffraction limited beams with intensities above 10^{24} W/cm^2 for the application of HB11 fusion, the radius of sphere 3 can be in the range of 0.1 millimetre for producing nuclear energy in the range of 100 MJ free of neutrons and with less radioactivity per gained energy than from burning coal.

This is the present status for potential realization of BH11 power stations as envisaged by Jak Kelly (Hora et al. 2009) following the comment of an expert in nuclear fusion at the Lawrence Livermore National Laboratory in California, S.W. Haan (2010) "This has the potential to be the best route to fusion energy".

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Highly Charged Ions and the Search for the Variation of Fundamental Constants

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Abstract

We discuss the search for a variation in the fine-structure constant α using highly-charged ions. In particular, we examine how highly-charged ions could be used to construct highly-accurate atomic clocks that could be used to detect the terrestrial variation of α due to the motion of the solar system relative to the observed "α-dipole". Furthermore, we show that highly-charged Fe and Ni ions in G191-B2B, a white-dwarf star could be used to probe non-linearities in the possible coupling of α-variation to the gravitational scalar potential.

Introduction

The idea to search for a variation in the constants of physics is not a new one. In fact, Dirac's Large Number Hypothesis was probably the progenitor of our fascination with the possible non-constancy of our physical constants (Dirac, 1937).

A measured variation in a constant with dimensions (units) is impossible to distinguish from a variation in the dimensions themselves. Therefore, we will limit our discussion to the dimensionless constants, namely, the fine-structure constant, $\alpha = e^2/\hbar c \sim 1/137$. Here e is the electron charge, $\hbar$ is the reduced Planck constant, and c is the speed of light.

The fine-structure constant is a physical constant that characterises the strength of the electromagnetic interaction. Analogies exist, such as $\alpha_G \sim 10^{-45}$, which characterises the strength of the gravitational interaction. As gravity is a much weaker interaction compared to electromagnetism, we see that α_G is very much smaller than α.

The quasar absorption spectra analysed by Webb et al. (2011) using data collected from the Keck and Very Large Telescopes (King et al., 2012) suggests that the fine-structure constant α takes on a gradient of values across the sky. This result has come to be known as the "Australian dipole" (Berengut and Flambaum, 2012).

Due to the motion of the Sun relative to the measured dipole (towards a region of larger α), the spatial gradient translates to a temporal variation of around $\dot{\alpha}/\alpha \sim 10^{-18} - 10^{-19}\,\mathrm{yr}^{-1}$ to an Earth-based observer, with a further small modulation incurred by the annual motion of the Earth around the Sun.

In order to detect this possible temporal variation, we turn to the most accurate instruments ever built – atomic clocks. The best current limit on terrestrial α-variation of $\dot{\alpha}/\alpha \sim (1.6 \pm 2.3)\times 10^{-17}\,\mathrm{yr}^{-1}$ was obtained by Rosenband et al. in 2008 by comparing Hg^+ and Al^+ optical atomic clocks. In their experiment, the transition used in the Hg^+ clock is strongly dependent on the value of α, whereas the transition used in the Al^+ is relatively insensitive.

As we note, their experimental result still falls about two orders of magnitude short of detecting the level of α-variation as predicted from astronomy. To confirm the dipole model of α-variation thus requires finding more sensitive systems, which is parameterised for an energy level within an atom or ion by

$$q = \frac{d\omega}{dx}\Big|_{x=0}, \tag{1}$$

where $x = \left(\alpha/\alpha_0\right)^2 - 1$ is the (small) fractional change in α^2 from its present value of α_0^2. Systems known to have large q values include optical clocks in Yb^+ (Porsev et al., 2009) and Th^{3+} (Flambaum and Porsev, 2009). In fact, an approximation for the sensitivity in Eq. (1) may be written as (Dzuba et al., 1999)

$$q \sim -I_n \frac{(Z\alpha)^2}{\nu(j+1/2)}, \tag{2}$$

where Z is the charge of the atom or ion, I_n is the ionization energy, ν is the effective principal quantum number, and j is the angular momentum of the energy level.

From Eq. (2), we see quickly why ions such as Yb^+ and Th^{3+} would be more sensitive to a variation in α – they possess combination of a larger nuclear charge and ionization energy compared to lighter ions such as Al^+ and Hg^+. In general, the more highly-charged the ion, the greater its sensitivity to a variation in α – a guiding principle we will use when searching for the most sensitive system later.

Eq. (2) can also be applied to searches for α-variation in astrophysical systems. By using spectral lines of highly-charged ions, we should be able to place more stringent limits on α-variation.

Flambaum and Shuryak (2007) suggest that the underlying mechanism for the variation of fundamental constants may be the coupling of the constants to scalar fields. An example of scalar fields is the gravitational potential. Highly-charged ions observed in systems with a much different gravitational potential than that available on Earth, such as white-dwarf stars, could be used to investigate such theories.

Level Crossings

As electrons are removed from atoms, the energy of transitions usually quickly grows out of the range of optical lasers. This necessitates the use of different types of spectroscopy, which can be up to 10 orders of magnitude less precise than optical spectroscopy, simply because optical spectroscopy is well-studied and widely used in the large majority of existing atomic clocks. Any gains in sensitivity to the variation of constants by using highly charged ions would quickly disappear unless a way to mitigate this problem is found. Thankfully, the phenomenon of level crossings may be used to solve this issue (Berengut et al., 2010).

A level crossing is the energy-reordering of two or more atomic levels within an atom or ion when one or more parameters are changed. This occurs because the ordering of energy levels initially follows the Madelung (periodic table) filling order. As electrons are removed from the atom, it begins to increasingly resemble atomic hydrogen, albeit with a larger nuclear charge. However, the order of energy levels in atomic hydrogen differs from that predicted by the Madelung filling scheme. This implies that upon removing a sufficient number of electrons from an atom, its energy levels will be reordered so as to reflect the energy level ordering in atomic hydrogen – a level crossing!

For ions near such level crossing points, the energy of transition of electrons between the crossing levels is small, and we find that optical transitions exist even in these highly-charged ions (see Figure 1). Therefore, by identifying ions near level crossings, we are able to preserve the gains in sensitivity to α-variation from using highly-charged ions and at the same time, retain the use of highly accurate optical spectroscopy.

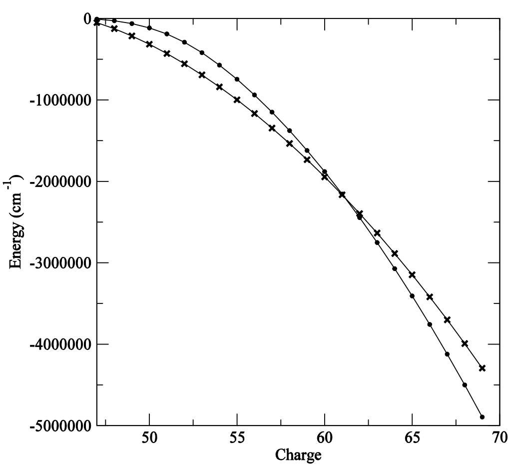

Figure 1: The energy of the 4f and 5s atomic orbitals for a 62 electron system against nuclear charge Z. The ordering of the energy levels switch near $Z = 77$.

Systematic effects in highly-charged ions

To achieve high-accuracy using atomic clocks in laboratories, experimentalists need to account for the systematic effects that affect the frequency of their atomic transitions very carefully. Examples of such effects that are routinely taken into account are the blackbody radiation shift, which accounts for the non-zero temperature of the system, and electromagnetic fields which cause Stark and Zeeman shifts.

There are two good parameterizations to describe a system's evolution from and towards the regime of highly-charged ions: isonuclear sequences (the number of electrons changes) or isoelectronic sequences (the number of protons changes). Whilst isonuclear sequences are how such ions would be produced in a laboratory, we find isoelectronic sequences more convenient for they allow more straightforward comparisons of fixed energy levels.

One further point to note is that the while the ion charge Z_i is a whole number, the external electrons that we are interested in "see" a screened (effective) charge Z_a instead. Relativistic effects would instead depend on the unscreened nuclear charge Z. One may turn to tables for values of Z_a to obtain estimates for these systematics.

The general trend is that the size of systematics tends to be much smaller than they would be for neutral atoms. This is because the electrons are more tightly bound to the nucleus, resulting in the relative size of external effects being much smaller when compared to the tighter binding.

Table 1: Scaling laws for highly-charged ions for various sources of systematic shifts in atomic clocks.

Effect	Scaling
2nd order Stark shift	$\sim 1/Z_a^4$
Blackbody shift	$\sim 1/Z_a^4$
2nd order Zeeman shift	Suppressed
Electric quadrupole shift	$\sim 1/Z_a^2$
Fine-structure	$\sim Z^2 Z_a^3/(Z_i+1)$
Hyperfine *A* coeff.	$\sim Z Z_a^3/(Z_i+1)$

Californium – the basis for a superior atomic clock

Based on our findings, we have identified highly-charged californium ions, Cf^{16+} and Cf^{17+}, as the most promising candidates for building atomic clocks that are both highly accurate and sensitive to the variation of α (Berengut et al., 2012). Californium is one of the heaviest elements with relatively long-lived isotopes that can be practically utilized in an atomic clock – this assures us the large charge and ionization energy as required for a large sensitivity in accordance with Eq. (2).

The lowest-lying energy levels as calculated using configuration interaction and many-body perturbation theory for Cf^{16+} are presented in Table 2. We see that the ion is near the 5f-6p level crossing, as the energies of the transitions between the two orbitals are well within the range of optical lasers. Table 2 also reveals that the transitions with the largest sensitivities to α-variation are two electron transitions between $5f^2$ states and $6p^2$ (the q value of a transition is simply the difference between the q values of the upper and lower levels) – of which the strongest are E2 and M1 transitions (ΔJ is at most 2). For comparison, the sensitivities of the transitions used in the Hg+ clock is $q \sim 50000\ \text{cm}^{-1}$, thus Cf^{16+} can potentially provide a factor of 13 improvement over the current-day best limits on α-variation.

Table 2: Selected energy levels of Cf^{16+} and their sensitivities to α-variation q.

Configuration	J	Energy [cm^{-1}]	q [cm^{-1}]
$5f^1 6p^1$	3	0	0
$6p^2$	0	5267	-370928
$5f^1 6p^1$	2	6104	106124
$5f^2$	4	9711	414876
$5f^1 6p^1$	4	24481	162126
$5f^2$	2	24483	354444
$5f^1 6p^1$	3	25025	59395
$5f^2$	5	29588	451455

Fe^{4+} and Ni^{4+} in White Dwarves

In this section, we will examine how highly-charged ions can be used to probe the relationship between the gravitational potential and the variation of □ (Maguijo et al., 2002). Theories (Berengut et al. 2013) write

$$\frac{\Delta\alpha}{\alpha} \equiv k_\alpha \Delta\phi = k_\alpha \Delta\left(\frac{GM}{rc^2}\right) \qquad (3)$$

for a dimensionless gravitational potential $\Delta\phi$ and a proportionality constant k_α.

Existing studies of the relationship between the variation of constants and their coupling to the gravitational scalar potential has been limited to Earth-based studies. These studies rely on the ellipticity in the Earth's orbit, which gives a 3% seasonal variation in the potential at Earth due to the Sun. Due to the high precision of atomic clocks, k_α can be determined despite the small variation in the gravitational potential ϕ.

The observation of Fe^{4+} and Ni^{4+} spectral lines in G191-B2B using the Hubble Space Telescope Space Telescope Imaging Spectrograph presents an opportunity to probe Eq. (3) in the regime of a much stronger gravitational potential – about 5 orders of magnitude larger.

This not only allows us to verify the coupling as described by Eq. (3), but it also allows us to probe any non-linearities that may arise in the coupling of α to ϕ which certain models predict (Bekenstein, 1982).

Fe^{4+} and Ni^{4+} also have relatively high ion charges – referring against to Eq. (2), any limits we place on α-variation using these ions would have an advantage over other spectra due to the innately higher sensitivities these transitions have to α. At the moment, our analysis of the results has been mainly limited by the lack of accuracy in the laboratory-measured spectra for these ions, which are needed to provide a reference for calculating the shift in relative positions of the lines in the astronomical spectra. The results as shown in Figure 2 reveal that the α-variation in G191-B2B is consistent with zero at the 1.05σ level.

Conclusion

The use of highly-charged ions in the search for the variation of fundamental constants has been shown to have much potential. Atomic clocks based on highly-charged ions would not only be highly-sensitive to a variation in the fine-structure constant, but would also result in more accurate clocks with smaller systematic errors. Highly-charged iron and nickel ions in white-dwarf stars also have the potential to probe the relationship between the gravitational potential and the variation of constants.

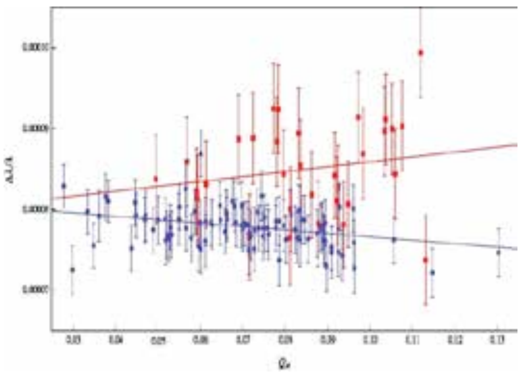

Figure 2: Scaled wavelength versus relative sensitivity to α-variation for Fe^{4+} (blue circles) and Ni^{4+} (red squares). The slope of the lines give $\Delta\alpha/\alpha = (4.2 \pm 1.6) \times 10^{-5}$ and $(-6.1 \pm 5.8) \times 10^{-5}$ for Fe^{4+} and Ni^{4+} respectively.

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Some aspects of the scientific development and astronomical research of Penny Sackett.

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Abstract

Penny Sackett was the Director of the Research School for Astronomy and Astrophysics at the Australian National University from 2002 to 2007 and is currently an Adjunct Professor at the same institution. She has made several significant contributions to dark matter in galaxies, galactic structure, microlensing and the search and characterisation of extrasolar planets. This paper looks at some aspects of the trajectory that led her to being appointed the Director of Mount Stromlo Observatory, one of Australia's internationally well known scientific institutions.

Keywords: Extrasolar planets, dark matter, galaxies, large optical telescopes

Introduction

Penny Sackett had a remarkable career that spanned three continents, viz: America, Europe and Australia. She belongs to a select group of scientific nomads who cross national borders seamlessly in the intellectual pursuit of the moving frontiers of astrophysics. She was the first woman scientist to become the Director of a major astronomical institution in Australia. She took over the Directorship of Mount Stromlo Observatory in July 2002. She was no stranger to Australia, as she had visited the country previously on her observation runs associated with her projects at the Anglo-Australian Observatory. What prompted her to apply for the Directorship, she said, "was the reputation of the people that worked there and also because of the place it held in world astronomy". She came with a vision. According to her, "The faculty that I inherited was stunning. You know, Bessell, Freeman, Peterson, Norris, Dopita and Schmidt. They were absolutely first rate, splendid teachers almost to a person and so really it was a matter of trying to reinvigorate that with some younger blood as well and watch the tradition continue".

Tragedy

However, even before she had time to settle down into her new job, tragedy struck. It was on a hot summers day on 18 January 2003 that fires engulfed Mount Stromlo and the Observatory. It was the most terrible catastrophe to befall the institution. The fires were so severe that they left a trail of devastation that had never been seen before. Only the charred remains of the once magnificent telescopes stood as silent witnesses in their burnt out domes including the $4 million Near Infrared Field Spectrograph (NIFS) that was undergoing final testing before being shipped to the Gemini North Telescope in Hawaii had been turned into a blackened melted mass. According to Sackett, "When the damage was assessed it was clear that we had lost all our research facilities – that is, all of our research telescopes on the mountain, all of our library facilities, and our workshop where we had built instruments for our telescopes and telescopes for other organisations". It was a difficult time for Sackett and a lesser person would have probably thrown his/her hat in and walked away. She stood her ground and began the rebuilding process with great determination and courage. She had to deal with a number of challenging and frustrating issues that not only involved the recalcitrant insurers, the keepers of the national heritage and staff morale. "The university put up some of its funds promptly, and the Federal government also gave $7.3 million to help us rebuild the workshops. So we were very grateful for that. That was probably the biggest issue, at least at the beginning", she said. The heritage issues were resolved with "really excellent compromises" so that a modern institution could operate within the constraints of a heritage listed building. As for staff morale, she continued, "I think as time went on, what became difficult was managing staff morale, because after the fire most people had, this sense of fight in them, that no, we're not going to let this get us down. No, this is not the end of Mount Stromlo Observatory. But when the rebuilding began to take much longer than people had anticipated, and when the insurance agencies were recalcitrant, it became a little bit harder to keep staff morale up".

Nevertheless, she pushed on. After the fires Sackett drew up a strategic plan for the years 2003 to 2007 in consultation with the staff to decide where the Observatory should be heading. This included, she said, "things like developing new leadership roles in the next generation of telescopes, increasing the number of graduate students that came to Mount Stromlo, increasing the efficiency of the telescopes at Siding Spring and supporting those that were most productive, expanding the breadth of the knowledge of the faculty, and maintaining and growing our instrumental and astro-engineering capacity".

Finding an astronomical niche

Sackett had arrived at Mount Stromlo with a track record of astronomical research and highly cited publications. Born in the small town of Lincoln, Nebraska she excelled in her studies at school and according to her, her secondary school physics teacher, "was instrumental in opening my eyes to the beauty and ubiquity, I would say, of physics, and without him I certainly would not have trained in physics later. He in fact taught us calculus just as a means to understand more physics". Her parents had only been trained at a vocational level and as they had not attended a university they were of not much help in guiding her in her career choice. However, her mother, she said, "was adamant about one thing, and that was that I should be trained in a way that I could earn my own living" and there was an expectation on the part of her parents that she would go to university. Having won a scholarship she attended the University of Nebraska in Omaha and as she went through university her "physics instructors became adamant that I should pursue a higher degree, which I hadn't thought of when I entered university", she said. After completing her undergraduate studies she enrolled for a PhD at the University of Pittsburgh which, according to Sackett, "was particularly well known at that time for its program in relativity and it had some very high powered general relativists". After graduating with a PhD in theoretical physics in 1984 from the University of Pittsburgh, it took her sometime to find a niche for herself. She completed her postgraduate studies at a time when there were very few women physicists in the US. It was difficult for women physicists to get jobs. Linda Schiebinger, a historian of science at Pennsylvania University notes that even as late as 1996 in the US the unemployment rate for women PhD physicists remained twice that of male peers (3.8% compared with 1.9%) after controlling for job experiences (Schiebinger 1999). According to Sackett, "It was difficult because there weren't very many women in physics. I think too that the networking opportunities simply weren't there. In general women were not mentored in the same way that men were mentored with respect to finding a job". There also seems to have been some prejudice against women in a highly male dominated discipline. The male locker room mentality was still prevalent in the US academic circles. In fact, this was also the case in Australian academic circles in the 1980s (Bhathal 1999). Sackett gives us a classic example of this. According to her, "I remember particularly once a famous scientist coming to visit when I was in graduate school, and the male graduate students were asked to go out to dinner with him, but I was asked to babysit one of the faculty's children so that he could go. I didn't do the babysitting, but then I didn't go to dinner either".

She worked at a number of jobs, viz: as a science journalist for *Science News*, as a teacher at Amherst College – a privately funded college attended by many of America's privileged minority, as a researcher at the Biological Sciences Department at the University of Pittsburgh and as a Program Officer at the National Science Foundation. Her breakthrough came when she won a small grant to study at the Kapetyn Astronomical Institute in the Netherlands, one of the major centres of astronomical research in the Netherlands. Some of the well known astronomers when she was there were Stuart Pottasch who was known for his work on planetary nebulae, and Renzo Sancisi and Tjeerd van Albada who were internationally recognised for their work on the distribution of dark matter in galaxies. The short stint provided her with the transition from being a theoretical physicist to becoming an observational astronomer.

Later her two years (1992 – 1994) at the Institute of Advanced Study at Princeton helped her to begin tying together several elements that she was interested in, viz: the structure and dynamics of galaxies which were related to dark matter. "And one way", she said, "to study dark matter is through microlensing. So all of these connections were sort of forged while I was at the Institute for Advanced Study in Princeton". Princeton she said was "extraordinarily important to me". It provided her with a springboard for the work she was going to do at the Kapteyn Institute where she worked for the next seven years. The work she did there centred exclusively around microlensing. It was during her time at Princeton that she realized "through the work of Bohdan Paczynski and Andy Gould that microlensing could be a way to look for planets, and not only the so-called MACHOS (Massive Compact Halo

Objects) that [were thought to] make up dark matter". So this was the direction she began to increasingly explore when she was at the Kapetyn Institute.

Extrasolar planets

Extrasolar planets around a Sun-like star were first discovered by the Swiss astronomers Michel Mayor and Didier Queloz in 1995. Mayor and Didier were hailed as the Galileo's of the 20th century and they opened up an area of research which has become very active and competitive. The method they had used is called the radial velocity or the Doppler technique. The more direct method is called the transit technique. In this technique the astronomers look for planets that partially eclipse the star that they are orbiting. This causes a temporary but periodic dip in the brightness of the parent star. However, Sackett employed the gravitational microlensing technique to search for extrasolar planets. It is based on the fact that gravity affects light, an idea that originated from Einstein. Unlike the microlensing method which is a statistical technique that can tell you about the planet population as a whole, the Doppler technique is a better method for studying individual planets. This is also true of the transit technique.

According to Sackett, "Gravity not only affects objects with mass, but it affects light. It can actually cause light to bend. And so when a massive object sits between a luminous object that's emitting light and a detector (an astronomer with a telescope) it can change the path of that light in such a way that more light reaches the observer than otherwise would, simply because there's some massive object sitting in-between. And that massive object is called a microlens, and you can think of it most often as just a normal star somewhere in the galaxy. It might be a star we can see, or it might be one we can't. If that star has a planet orbiting it, then the gravitational field will not just be the gravitational field of the star but the gravitational field of the star plus the planet. It's not so important that the field is stronger, because after all the planet is just a tiny fraction of the total mass of the star, but the distribution of that gravitational field is different. And that means that as a bright object such as a background star sends its light to the telescope, and it's moving as it does so because everything in the galaxy moves, it probes different parts of this gravitational field, which looks different in different places because of the presence of the planet. We can do what's called 'inverting' that problem by taking the light curve that we observe with the telescope and deducing what the gravitational field must have been, and in particular whether it was due to a planet orbiting a star. The remarkable thing about microlensing is that you don't even have to see the star that the planet is orbiting in order to detect planets. You're using the natural effect of the lensing that Einstein talked about to create a telescope that is more powerful than the ones you actually have available to you here on Earth".

In the same year (1995) that Michel Mayor and Didier Queloz discovered the first planet going around a normal star, Sackett formed the PLANET collaboration which consisted of astronomers from various parts of the world to provide continuous time coverage. One of her motivations for forming this team was the "possibility of being the first to detect an extrasolar planet", Sackett, said. However, the honour was to go to Mayor and Didier. Her second reason for getting involved in this venture was the fact that through studying dark matter she and her collaborators were confident that they could understand the microlensing signal. The chance to find out whether they understood the microlensing technique in their search for extrasolar planets came from their observations of the binary microlens MACHO–1997–BLG–41. According to Sackett, when they analysed their data they found that what they were seeing was "not a planet and a star but a double star system" (Albrow et al. 1998). By itself this was not extraordinary. What was extraordinary was the fact that they could "deduce this just from the microlensing light curve alone". This gave them confidence in their ability to understand and use the technique.

Ten years after she founded the PLANET collaboration, Sackett and her colleagues discovered a cool planet 5.5 Earth masses through gravitational lensing (Beaulieu et al. 2000). This discovery, she said, took them ten years rather than the five that she had hoped. It was an exciting discovery since up to that time no planet that was more like an Earth-like planet had been found. Most of the planets that had been discovered up until this time, she said, "were 100 to 300 times the Earth's mass". With the advent of the Kepler mission many more potential planets have been found that are more Earth-size. Since the last Kepler catalogue was released in 2012 the number of candidates discovered in the Kepler data now totals 2740 potential planets orbiting 2036 stars. The most dramatic increases are seen in the number of Earth-size and super Earth-size candidates discovered, which grew by 43% and 21% respectively.

Dark matter

Her observations of MACHO-98-SMC-1 in the Small Magellanic Cloud provided an interesting insight into MACHO (Massive Compact Halo Objects) events and dark matter. At the time they were doing this research, one of the big questions that microlensing was expected to answer was whether the dark matter was made up of small, compact objects, such as dead stars or Jupiters or some unknown objects that could cause a microlensing event. Many astronomers at that time were looking at stars in the Magellanic Clouds and seeing whether the light from them exhibited a microlensing curve as if there was a dark, unseen microlens between the observer and the Clouds. Whenever they received warning from microlensing teams that a microlensing event was in progress, they could immediately turn their telescopes to it. In the case of MACHO-98-SMC-1, they obtained an absolutely stunning light curve, Sackett said. According to her, "this was good enough for us to detect small things in this light curve that weren't (at least at that time) typically observed. And those included being able to tell when one part of the background star passed a particular point in the gravitational pattern, compared to when a different part of the star crossed". This allowed them to measure among other things the proper motion of the microlensing event. What they found, she said, "that alas, in this particular event, it wasn't some mysterious dark matter that was causing the microlensing, it was in fact a typical star in the Magellanic Clouds" (Alfonson et al. 2006).

A lot of hard work goes on into researching a problem. Quite often one goes down wrong paths and dead ends. However, sometimes one is rewarded like Archimedes with a Eureka or "aha" moment. This happened to Sackett. According to her, "it relates back to this problem of dark matter

– it had been suggested by some that indeed the dark matter in our Galaxy must be in the form of these MACHOs (Compact Halo Objects) that cause microlensing, and that in fact a colour magnitude diagram would actually show the population of these objects, some of which were stars. Now, what I mean by a colour magnitude diagram is that you plot the brightness of the star on one axis and the colour on the other, and if the objects are all the same age and same distance, then there'll be a pattern that develops on this plot that's quite characteristic. But if some of the stars are a little bit closer, and therefore, say, not in the Magellanic Clouds but between us and the Magellanic Clouds, then they would show up at a slightly different place on the colour magnitude diagram. And it was proposed that something like this was actually seen". There were several reasons why this suggestion bothered Sackett. "It was such a simple idea. It seemed to be there for all to see, this extra little addition in the colour magnitude diagram", she said. She was working at the Kapteyn Institute at the time, and in order to go up to the second floor where she worked she had to walk by the rack of new journals that had just come in. And on the cover of one of them was new data from the Hipparcos satellite showing the colour magnitude diagram not of the Large Magellanic Cloud but of the nearby stellar neighbourhood. And in that, she saw the very same additional feature. And that, she said, "was my aha moment, because I realised, this has nothing to do with the Large Magellanic Cloud. It has nothing to do with intervening objects that are in-between us in the Cloud. Nothing to do with dark matter. It actually has to do with stellar evolution. There is a period in stars' lives when they occupy this particular part of the colour magnitude diagram, and how many stars are there depend on how old the different populations are. And so with a postdoc we took many colour magnitude diagrams that he already had for the Large Magellanic Cloud. We analysed them this way, we showed that this extra feature was exactly where you would expect it to be, and it was occupied with precisely the number of stars you would expect it to be given the LMC's star formation history" (Beaulieu and Sackett 1998). "That aha moment", she continued, "was seeing in a completely different context the same signal, and therefore immediately knowing that this explanation was different than what had been originally proposed".

Galaxies

Over the last two decades, several studies have been conducted to understand the evolution of galaxies. For example, there has been a realisation that interactions between galaxies may play an important role, and observations have also been made of shells and rings around elliptical galaxies. Sackett and her colleagues carried out new observations and produced a photographic atlas of polar ring galaxies (Whitmore et al. 1990). Some astronomers were interested in the history of these galaxies and wanted to know what happened to these odd looking objects. Her interest in these fascinating galaxies arose from her desire to study the shape of dark matter haloes and how dark matter was distributed. The way astronomers deduced the presence of dark matter in galaxies was largely through rotation curves. They measured the speed of individual stars in the galaxy as a function of how far away they are from the centre, and this told them how much force they were experiencing and therefore how much mass the galaxy has that is acting upon that particular star or set of stars. This is how astronomers became confident that there must be more mass in the galaxy than we can see and there must be dark matter. With Linda Sparke, Sackett studied the polar ring galaxy NGC 4650A. She did this study when she was at the Kapetyn Institute for the first time on a small grant from the National Science Foundation. NGC 4650A is a strikingly beautiful object which has a central body of older stars in the middle, somewhat flattened into an elliptical shape. This is surrounded by a gigantic ring of gas and much newer stars that are orbiting in a completely perpendicular plane to the way the stars were orbiting in the central object.

They studied this galaxy because they could measure the rotation curve not only in the plane of the central body where there were stars but also in a plane perpendicular to it where there were stars and gas they could use for their analysis. According to Sackett, by studying these "you could ask the question: Do these two curves look the same because the distribution of matter is spherical? If this was the case it would not matter in which direction you looked because the gravitational field would be spherical. Or does the polar ring have a different rotation curve to that of the central body, which might indicate that the dark matter preferentially lies in one plane or the other" (Sackett and Sparke 1990).

From a more detailed analysis of the motions of the stars in this galaxy, Sackett said, "we found, after taking into account elliptical orbits and all sorts of other things, that the rotation curve of the stars and gas in the polar ring is different than that in the central region. That immediately tells you that the total gravitational mass is not spherically distributed". They knew that some of the matter is not spherically distributed because the galaxy's flattened and it has a ring. So one had to be more careful than that and they needed to subtract the effects of the mass they could see, and then ask themselves, of the mass that is left over, how is it distributed? "And the answer", Sackett said, "was as near as we could tell within the precision of our measurements that the dark matter was also flattened – not as thin as a stellar disk, but sort of as flat as a rugby ball or something like that". This work was important for those astronomers who were trying to understand what dark matter was made of, because certain proposals for dark matter were calling for a very flattened disk while others were calling for an absolutely spherical distribution. She said, they gave them "something in-between" (Sackett et al. 1994).

In her study of the spiral galaxy NGC 5907 she found a faint luminous halo around the galaxy. What surprised her and her colleagues was that the distribution of this light was more extended than had been previously recognised. It did not fall off as sharply as one typically expected in stellar haloes. According to her, "we asked the obvious question – is the light distributed the way we think dark matter is distributed? Because if it was, maybe there was a connection between this light we were seeing and dark matter". *Nature*, the British scientific journal decided to make it the cover story (Sackett et al. 1994) and it landed them in a controversy. Their critics began saying that Sackett and her colleagues were claiming that they had "found what dark matter was", despite the fact, she said, "that they were as cautious as they could possibly be in the write up of their abstract". Nevertheless, one of the benefits of this controversy was that it prompted other astronomers "to look for faint light around other galaxies, and it was found in many other galaxies as well", Sackett said. According to Sackett, "when people looked deeper, what they discovered was that it wasn't smoothly distributed but was often on streamers that were at great distance from the primary galaxy. And some of the new thinking (and no doubt this will be modified in time as well) is that this faint distributed light is in the outskirts of galaxies where the dark matter is because it's caused by satellite galaxies that have dropped into the potential well of the primary galaxy and slowly over time have had their stars stripped away into beautiful long tails that surround the primary galaxy".

Instruments for Studying the Universe

One of the major agenda items on Sackett's plate after the fires was to rebuild the workshops. From its beginnings in the 1920s, the workshops had always been an integral part of Mount Stromlo. Many of the instruments that had been used to make significant astronomical discoveries were based on the instruments that were designed and constructed in the workshops which has excellent technical staff. A modern up-to-date Advanced Instrumentation Technology Centre (AITC) was built in stages. Sackett was responsible for the building of Stage 1 which was opened in 2006. According to Sackett, "the goal of the Centre was to replace the activities that took place in the workshops at Mount Stromlo that were destroyed in the fire. Furthermore, she built the Centre for the future. It had a large integration and assembly hall attached to the electrical and mechanical design workshops and laboratories. The integration hall and the laboratories have been designed to cater for the next generation of instruments expected to be installed on Extremely Large Telescopes currently being planned by international consortia".

The Observatory had acquired a contract to build the Near-infrared Integral Field Spectrograph (NIFS) for the Gemini North telescope. However, as mentioned earlier, it was completely destroyed by the fires just before it was to leave the workshops for Hawaii. NIFS 2 was rebuilt by the Canberra based aerospace company, Auspace Ltd, in collaboration with Mount Stromlo designers and engineers. The completed instrument was shipped to Hawaii in August 2005 and installed on the Gemini North 8.1 metre telescope in October. Jan van Harmelen, the NIFS Project Manager and Peter McGregor, the Project Scientist spent a month at the Gemini North Observatory supervising the tests and the initial observations. First observations on the Gemini North telescope, she said, "showed unprecedented spatial and spectral detail in otherwise dust-obscured regions, allowing young stellar wind speeds and black hole masses to be measured. The whole project was a great success and a credit to the technical and scientific staff at Mount Stromlo Observatory".

The Observatory also secured a contract to build the Gemini South Adaptive Optics Imager (GSAOI) for the Gemini 8 metre telescope in Chile. This is a near-infra-red camera which is being used with Gemini's flagship Multi-Conjugate Adaptive Optics (MCAO) system on the Gemini South 8 m diameter telescope in Chile. The MCAO system corrects the blur due to the Earth's atmosphere over a wide field than has previously been possible. GSAOI records diffraction-limited images of astronomical objects with 0.02 arcsecond sampling over its full 85 x 85 arcsecond field of view. "The GSAOI was designed and built by a team of engineers led by Peter McGregor. The team included John Hart, Dejan Stevanovic, Gabe Bloxham, Damien Jones, Jan van Harmelen, Jason Griesbach, Murray Dawson, Peter Young and Mark Jarnyk. The camera was shipped to the Gemini South telescope in Chile in October 2006".

Another instrument that was approved for construction in December 2005 was the Wide Field Spectrograph (WiFeS). It provides 950 simultaneous spectra throughout the optical frequency range. It has been installed on the 2.3 m telescope at Siding Spring. It has a data gathering capability of 10 to 100 times the rate of conventional spectrographs. In the same year Brian Schmidt's highly innovative telescope called the SkyMapper was approved for fabrication. "It is a 1.35 metre diameter telescope located at Siding Spring Observatory. It is a new breed of dedicated survey telescopes that will conduct the Stromlo Southern Sky Survey which will produce the first deep digital map of the entire southern sky. The design was produced by Conroy, Granlund and Oates", according to Sackett.

After the fires the astronomers had a long and hard think about what they wanted in terms of telescopes for the future. It would have been an easy exercise for them to go down memory lane and recreate what they had lost. But Sackett had rather bold ideas about what they should be looking for in terms future telescopes for Mount Stromlo. According to Sackett, "we thought that one of the legacies we would like to leave is that the future generation would have a facility that was to them what the AAT (Anglo-Australian Telescope) was in the 1970s and 1980s, namely, one of the biggest telescopes in the world that would be capable of doing things that otherwise weren't possible, but also a telescope that was reasonably versatile, that could have a variety of instruments and do different sorts of astronomy". Her biggest coup was to get Mount Stromlo involved in planning the world's next generation very large optical telescopes, called the Giant Magellan Telescope (GMT). The building to enclose the telescope will be as high as a 23-story sky scraper. The instrument will have ten times the resolution of the images from the Hubble Space Telescope. It will be a time machine which will allow astronomers to probe the darkest reaches of the universe and ask questions such as, when did the first stars, galaxies and black holes form?

Sackett had the audacity and courage to propose Mount Stromlo Observatory becoming involved in the effort to build the GMT. It was the best and far reaching decision she made for the future of Mount Stromlo Observatory and Australian astronomy. She signed the Memorandum of Understanding in Texas on behalf of the Australian National University. By signing the document, Mount Stromlo joined an elite group of teaching and research institutions in the US (Carnegie Institution of Washington, Harvard University, Massachusetts Institute of Technology, the University of Arizona, the University of Michigan, the Smithsonian Institution, the University of Texas at Austin and the Texas A& M University) to undertake the detailed design of the telescope. It will have six segments, each 8.4 metres in diameter surrounding a seventh mirror of the same size. The total light gathering power will be nearly seven times that of the Gemini telescopes.

The science objectives, Sackett, said, "will be many, because it is meant to be a multi-purpose telescope. But in particular, the image quality of this telescope is something that is of prime concern, so that using a method called adaptive optics, which can undo the blurring caused by movement in the atmosphere, this telescope should be able to not only take pictures that are as crisp as those of the Hubble Space Telescope but in fact much crisper. That means seeing more detail. It means being able to pull out faint, very distant objects from the background or from brighter foreground objects. That means finding more distant stars in the early universe. It means being able to actually see those planets orbiting other stars, detecting the light from the planets themselves, and thereby being able to analyse the atmosphere, for example, of those planets, which I think will be tremendously exciting". She hopes that construction may begin as early as 2014, assuming adequate funding becomes available.

Funding and research output

2002 was the first full year that astronomers from the Research School for Astronomy and Astrophysics were able to compete for ARC funding. "They were very successful in their grant applications winning over $2.7 million. Over 50% of the School's funding was derived from the increasing success of the School's astro-engineering design and fabrication teams". The arrival of Sackett at the Observatory in 2002 also brought in the new field of extrasolar planets into the traditional astronomy programs pursued by the Observatory. Together with the Research School of Earth Sciences, Sackett established a new Planetary Science Institute in 2002. According to Sackett, the Institute was "designed to cultivate a research program of planetary science combining the detailed studies possible in our Solar System with the recent wealth of information from the young field of extra-solar planets".

Despite the fires the Observatory "remained very active in research, publishing over 500 papers in refereed international journals", according to Sackett. The research effort spread over a number of speciality areas, viz: solar and extrasolar planetary systems, stars and stellar populations, the Milky Way and galaxies, dark energy and dark matter, gamma ray bursts, interstellar medium and galactic feedback, and adaptive optics.

Conclusion

Sackett achieved most of what she had set out to accomplish in her five year term. She had, as she planned reinvigorated the institution and continued the growth of the tradition of excellence. She steered the Observatory for a new beginning. Her decision to embark on the Great Magellan Telescope was the boldest, audacious and most visionary decision she made. She will be remembered in ages yet to come for her future vision for Mount Stromlo Observatory and Australian astronomy in the era of very large telescopes that will provide us with discoveries that we have yet to imagine. In 2007 Sackett completed her term as the Director of Mount Stromlo Observatory to take up in 2008 the position of Chief Scientist for Australia.

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Thesis abstract

The flow around a fish-inspired heaving and pitching hydrofoil

Timothy Lau

Abstract of a thesis for a Doctorate of Philosophy submitted to
The University of Adelaide, Adelaide, Australia

An extensive investigation into the flow around a fish-inspired heaving and pitching hydrofoil was performed using a combination of two dimensional digital particle image velocimetry (PIV), direct strain gauge force and moment measurements, dye visualisation and hydrogen bubble visualisation. The intention of this investigation was to study the effect of the foil dynamics on the foil wake structure and hydrodynamic forces, with the ultimate goal of determining if the oscillating foil, and by implication, fish, employ unsteady flow mechanisms to generate optimal thrust.

The experiments were performed by systematically varying the foil non-dimensional heave-amplitude-to-chord ratio, h_0/c=0.25-0.75, the foil pitch amplitude, θ_0=0-45°, and the free-stream velocity, U_∞. The phase difference between the pitching and heaving motion was fixed at ψ=90° (heave lagging pitch). Experiments consisted of 113 different flow cases for dye visualisation, 38 flow cases for hydrogen bubble visualisation and 108 flow cases for simultaneous PIV and force measurements. The resultant Strouhal numbers, based on the heave amplitude, fall into the range $0.1 \leq St_h \leq 1$ while the Reynolds numbers, based on the foil chord length, were approximately Re=500-12,500.

The experimentally measured time-averaged thrust coefficient, C_t, obtained independently using PIV and direct strain gauge measurements, shows excellent agreement, and indicates that very large values of C_t>10 can be generated by the foil, particularly when the non-dimensional heave amplitude is large relative to the pitch amplitude, and St_h is large. The results also indicate that in all investigated cases, there is no sign of a sudden loss in lift that is associated with the "stall" phenomenon usually seen in steady foils, even when the unsteady foil achieves very large instantaneous angles of attack (α_{max}>60°).

To obtain a context for comparison, a quasi-steady model (Q-S model) of the oscillating hydrofoil was developed, based on the assumption that the flow around the unsteady foil at any given instant is equivalent to the flow around an identical steady foil with the same angle of attack. For most foil dynamic parameters and flow conditions, the value of C_t predicted by the Q-S model shows excellent agreement with the results obtained experimentally. However, when h_0/c is large compared to θ_0, the experimentally measured values of C_t far exceed the theoretical predictions. This suggests that the oscillating foil employs unsteady flow mechanisms to augment thrust production when h_0/c is large relative to θ_0.

Flow visualisation of the foil wake indicates that different wake patterns are produced, depending on the flow conditions. The observed wake patterns are interpreted as a combination of "primary" vorticity, which is associated with the production of lift (and hence thrust) by the foil, and "secondary" vorticity, which is associated with the drag produced by the foil. During each foil half-cycle, secondary vorticity manifests itself as multiple vortical roll-ups ("S" vortices), whereas the primary vorticity sheds as a single, typically large vortex, which combines with adjacent "S" vortices to form one "P" vortex. When h_0/c is large compared to θ_0, these "P" vortices are observed as very large leading edge vortices with strong spanwise flow (towards the foil centreline). These leading edge vortical structures are further evidence that the foil employs unsteady flow mechanisms to generate large thrust coefficients.

Based on the positions of these "P" and "S" vortices in the wake, we define three distinct wake regimes, a) "Drag regime", occurring at $St_h \leq 0.15$, b) "Transitional regime", occurring at $0.15 < St_h \leq 0.3$ and c) "Thrust regime", occurring at $St_h > 0.3$, whereby each regime produces subtly different wake patterns.

The wake behind the foil was also analysed quantitatively by measuring the first moment of circulation of the foil wake, which is defined as the product of the total circulation generated by the foil (of any given sign) per cycle and the wake width based on the centroids of the shed vorticity. In an important finding, it is shown that the data for C_t vs. the first moment of circulation collapse onto a single curve, regardless of flow conditions and foil dynamic parameters. For most (≈95%) of the cases measured, it is shown that C_t is approximately linearly proportional to the moment of circulation, indicating that the thrust produced by the foil can be increased by generating large vortical structures and/or increasing the wake width.

Based on these results, we therefore conclude that the foil employs unsteady flow mechanisms only when h_0/c is large relative to θ_0. Under these conditions, large thrust coefficients are generated by the foil due to the generation of leading edge vortical structures with large circulation, which are positioned far away from the foil time-averaged centreline.

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Thesis abstract

Ontogenetic ecophysiology of secondary hemi-epiphytic vines

Yansen

Abstract of a thesis for a Doctorate of Philosophy submitted to
James Cook University, Townsville, Australia

Secondary hemi-epiphytes start their life as ground-dwelling plants. Like other vines, the plant then climbs the host, but when the plant reaches maturity, the oldest portion of the stem dies. The plant then loses its stem connection to the soil and becomes semi-epiphytic. However, true secondary hemi-epiphytism is probably not as common as thought, since, in most cases semi-epiphytic vines reconnect to the soil through aerial roots. The change in soil connection during the ontogeny of these species may have physiological and anatomical consequences. As they eventually live in the canopy environment, it is feasible that secondary hemi-epiphytes might develop adaptations to cope with the stressful canopy environment, especially water stress during dry periods. However, there is a lack of understanding on the ecophysiology of secondary hemi-epiphytes in rainforests.

There is a paucity of information on the anatomy and physiology of secondary hemi-epiphytes, once they lose their stem connection to the soil, compared with the terrestrial early stage of development. To address this knowledge gap, characteristics of stem water transport, leaf anatomy and physiology, and soil water resource partitioning were examined in this research. Two species were selected for the study: *Freycinetia excelsa* F. Muell (Pandanaceae) and *Rhaphidophora australasica* F.M. Bailey (Araceae), which occur naturally in the Wet Tropics area of north Queensland. The general objective of this research is to better understand the ecophysiology of secondary hemi-epiphytes during their ontogenetic development.

The capacity of *F. excelsa* and *R. australasica* stems to conduct water differed between plants of different developmental phases. Adult individuals of *F. excelsa* and *R. australasica* had wider vessels than younger plants. Hydraulic architecture parameters, i.e. hydraulic conductivity, stem specific conductivity and leaf specific conductivity, were also higher in adult plants than for intermediate and juvenile individuals. These results indicate that adult plants had a higher capacity to conduct water through the stem to the leaves than did individuals at an earlier stage of development.

As the plants became more mature and longer, they tended to have low hydraulic conductivity at the stem base. This finding is supported by the fact that the size of xylem vessels was found to decrease in the basipetal direction: the base of the stem had narrower vessels than the middle part of the stem. However, the low hydraulic conductivity at the base of the stem may also be related to the fact that monocotyledonous plants lack secondary development. Therefore, the stem base contains the oldest shoot tissues and the vessels might be less functional. Wider vessels and higher hydraulic conductivity in adult individuals of *F. excelsa* and *R. australasica* show that the change in plant-soil connectivity during ontogeny of these species does not physically restrict water transport.

Adult individuals of *F. excelsa* and *R. australasica* had larger stomata than conspecific juveniles. However, adult plants also had more stomata per unit area, which gives them more control of the opening and closing of stomata in certain areas of the leaves. These characteristics of leaf anatomy suggest that secondary hemi-epiphytes are well-adapted to the canopy environment.

Juvenile plants of these two study species appear to be more sensitive to the onset of drought than plants of later developmental stages. Within each dry and wet season, the water potential of leaves from all growth forms were similar but the patterns of daily CO_2 exchange differed, with CO_2 uptake by juvenile plants most affected by dry season conditions. However, the CO_2 exchange rates were similar for adult, intermediate and juvenile plants during the wet season. High water availability in the wet season and relatively low evaporative demands provide excellent conditions for plants to absorb CO_2. The significant down-regulation of CO_2 exchange in the dry season in the juveniles is related to the lower hydraulic conductivity of their stems. Water supply to juveniles may be restricted during the dry season, such that down-regulation of CO_2 uptake and stomatal opening are necessary to diminish water loss and maintain water potential. Water supplied to intermediate and adult plants by aerial roots growing from a number of places along the stem is evidently sufficient to sustain higher rates of CO_2 exchange and water loss.

Plants of different ontogenetic stages had different behaviours towards soil water resources. Based on the hydrogen stable isotopes of water derived from different layers of the soil profile, matched with isotope signatures of the stem water, water uptake by juvenile individuals was limited to the area near the soil surface; on the other hand, adult plants utilized water from all soil layers studied. This consequently affects the capacity of plants to exploit all available soil water sources across seasons, which influences the performance of individuals of different ontogenetic stages in response to environmental conditions.

Variations in the ecophysiological attributes of the secondary hemi-epiphytes *F. excelsa* and *R. australasica* indicate differences in the ability of these plants to survive during their development. This study showed that smaller size juveniles may have a higher potential susceptibility to stressful environmental conditions compared to larger adult congeners. Based on ecophysiological characters, these two secondary hemi-epiphytic have not adapted especially to the epiphytic habit as they climb the host and live in the canopy. The plants' soil connections through aerial roots provide access to soil, avoid the stem basal hydraulic bottle neck and contribute to more options for soil water resource acquisition.

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The Royal Society of New South Wales

The Clarke Medal 2014

The Clarke Medal was established to acknowledge the contribution by the Rev William Branwhite Clarke MA FRS FGS, Vice-President of the Royal Society of New South Wales from 1866 to 1878 The Medal is awarded annually for distinguished work in a natural science done in Australia and its Territories.

The Medal is awarded by rotation in the fields of geology, botany and zoology. This year's award is in the field of geology in all its aspects. Nominations are called for the names of suitable persons who have contributed significantly to this science.

Nominations should include a list of publications, a full curriculum vitae and a statement clearly indicating which part of the nominee's work was done in Australia and which part was done overseas.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

In cases where the Council of the Society is unable to distinguish between two persons of equal merit, preference will be given to a Member of the Society.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

Only electronic submissions will be accepted. Nominations and supporting material must be submitted to the Honorary Secretary at secretary@royalsoc.org.au no later than **30 September 2014**.

The winner will be announced and the Medal presented at the Annual Dinner of the Royal Society scheduled to be held in 2014. The winner will be notified at least two weeks beforehand.

The Royal Society of New South Wales

The James Cook Medal

The James Cook Medal was established in 1947 with funding by Henry Ferdinand Halloran. Halloran, who had joined the Society in 1892 as a 23 year-old, was a surveyor, engineer and town planner. He did not publish anything in the Society's Journal but he was a very enthusiastic supporter of research. Halloran funded what were to become the Society's two most prestigious awards, the James Cook Medal and the Edgeworth David Medal, the latter being the medal for young scientists.

The James Cook Medal is awarded at intervals for outstanding contributions to science and human welfare in and for the Southern Hemisphere.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

Only electronic submissions will be accepted. Nominations and supporting material must be submitted to the Honorary Secretary at secretary@royalsoc.org.au no later than **30 September 2014**.

Should the Medal be awarded, the winner will be announced and the Medal presented at the Annual Dinner of the Royal Society of NSW to be held in 2014.

The Royal Society of New South Wales

Walter Burfitt Prize 2014

The Walter Burfitt Prize was established as a result of a generous gift to the Society by Dr W.F. Burfitt BA MB ChM BSc of Sydney, which was augmented by another gift from Mrs W.F. Burfitt when Dr Burfitt died in 1957. The Prize was further augmented in 2004 by a gift from Dr Burfitt's grand-daughter Mrs A. Thoeming.

The Prize is awarded at intervals of three years to a worker in pure or applied science, resident in Australia or New Zealand, and whose papers and other contributions published during the past six years are deemed of the highest scientific merit. Account is taken only of investigations described for the first time, and carried out by the author mainly in these countries.

Nominations should include a list of publications, a full curriculum vitae and a statement clearly indicating which part of the nominee's work was done in Australia or New Zealand and which part was elsewhere.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

In cases where the Council of the Society is unable to distinguish between two persons of equal merit, preference will be given to a Member of the Society.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

Only electronic submissions will be accepted. Nominations and supporting material must be submitted to the Honorary Secretary at secretary@royalsoc.org.au no later than **30 September 2014**.

The winner will be announced and the Medal presented at the Annual Dinner of the Royal Society scheduled to be held in 2014. The winner will be notified at least two weeks beforehand.

The Royal Society of New South Wales

The Edgeworth David Medal 2014

The Edgeworth David Medal, established in memory of Professor Sir Tannatt William Edgeworth David FRS, a past President of the Society, is awarded for distinguished contributions by a young scientist.

The conditions of the award of the Medal are:

- The recipient must be under the age of thirty-five years at 1st January, 2013.
- The Medal will awarded be for work done mainly in Australia or its Territories or contributing to the advancement of Australian science.

Nominations are called for the names of suitable persons who have contributed significantly to science, especially the scientific aspects of agriculture, engineering, dentistry, medicine and veterinary science.

Agreement of the nominee must be obtained by the nominator before submission and included with the nomination.

The winner will be expected to write a review paper of their work for submission to the Society's Journal and Proceedings.

Only electronic submissions will be accepted. Nominations and supporting material must be submitted to the Honorary Secretary at secretary@royalsoc.org.au no later than **30 September 2014**.

The winner will be announced and the Medal presented at the Annual Dinner of the Royal Society of NSW to be held in 2014.

The Warren Prize 2014

The Warren Prize has been established by the Royal Society of NSW to acknowledge Professor William Henry Warren's contribution both to the Society and to the technological disciplines in Australia and internationally. In 1884, Professor Warren established the first engineering faculty in New South Wales at the University of Sydney and was appointed as its Professor. He was President of the Royal Society of New South Wales on two occasions. He had a long career of more than 40 years and during this time was considered to be the most eminent engineer in Australia. When the Institution of Engineers, Australia was established in 1919, Professor Warren was elected as its first President. He established an internationally respected reputation for the Faculty of Engineering at the University of Sydney and published extensively, with many of his papers being published in the *Journal and Proceedings of the Royal Society of New South Wales*.

The aim of the prize is to recognise research of national or international significance by engineers and technologists in their first two decades or so of professional practice. The research must have originated or have been carried out principally in New South Wales. The prize is $500.

Entries are by submission of an original paper written to academic standards. The paper should review the research done and identify its national or international significance. Preference will be given to entries that demonstrate relevance across the spectrum of knowledge – science, art, literature and philosophy – that the Society promotes.

Only electronic submissions will be accepted. Papers may be submitted via e-mail to the Society at this address: editor@royalsoc.org.au. Entrants are referred to "Information for Authors" available from the Society's web-site at URL:
http://www.royalsoc.org.au/publications/author_info.html

Entries for the 2014 award close on **30 September 2014**.

The winner will be announced and the Prize presented at the Annual Dinner of the Royal Society of NSW to be held in 2014.

The Royal Society of New South Wales History and Philosophy of Science Medal 2014

The Royal Society of NSW History and Philosophy of Science Medal was established in 2014 to recognise outstanding achievement in the History and Philosophy of Science. It is anticipated that this prize, like the Society's other awards, will become one of the most prestigious awards offered in Australia in this field.

Persons nominated will have made a significant contribution to the understanding of the history and philosophy of science, with preference being given to the study of ideas, institutions and individuals of significance to the practice of the natural sciences in Australia.

Entries may be made by nomination or direct submission. All entries should be accompanied by a full *curriculum vitae* and include a one-page statement setting out the case for award. In the case of nominations, the agreement of the nominee must be obtained by the nominator before submission and included with the entry.

The winner will be expected to submit an unpublished essay, drawing on recent work, which will be considered for publication in the *Journal and Proceedings of the Royal Society of New South Wales* during the following year.

Only electronic submissions will be accepted. Entries and supporting material should be submitted by email to the Royal Society of New South Wales, marked to the attention of the Honorary Secretary (secretary@royalsoc.org.au), no later than 31 December 2014.

The winner will be announced and the Prize presented at the Annual Dinner of the Society to be held in 2015. The winner will be notified in February 2015.

The Royal Society of New South Wales

Royal Society of NSW Scholarships 2014

The Royal Society of NSW Scholarships are funded by the Society to recognise outstanding achievements by early-career individuals working in a science-related field.

Applications for Royal Society of NSW Scholarships are sought from candidates working in a science-related field in New South Wales or the Australian Capital Territory. Up to three Scholarships will be awarded each year. Applicants must be enrolled as research students at a University in NSW or the ACT, and must be Australian citizens or Permanent Residents of Australia.

The award consists of a certificate acknowledging your achievement, a $500 prize and a free one-year of membership of the Society. The winners will be expected to deliver a short presentation of their work at the Monthly Meeting of the Society and to prepare a short paper for the Society's Journal.

For further information and inquiries please contact the Society at info@royalsoc.org.au.

Applicants should email their submission to: secretary@royalsoc.org.au **by 30 September 2014**.

The winners will be invited to make a presentation on their work at the first Society's first meeting in 2015.

Archibald Liversidge:
Imperial Science under the Southern Cross

Roy MacLeod

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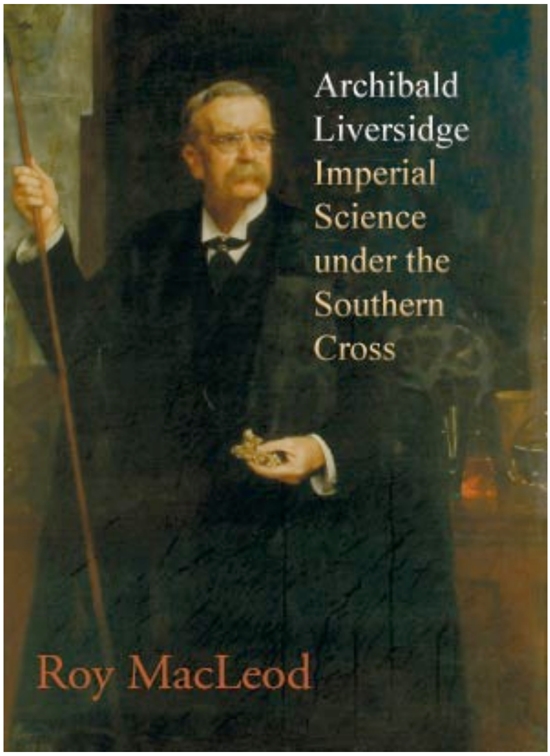

When Archibald Liversidge first arrived at the University of Sydney in 1872 as Reader in Geology and Assistant in the Laboratory, he had about ten students and two rooms in the main building. In 1874, he became Professor of Geology And Mineralogy and by 1879 he had persuaded the University Senate to open a Faculty of Science. He became its first Dean in 1882.

In 1880, he visited Europe as a trustee of the Australian Museum and his report helped to establish the Industrial, Technological and Sanitary Museum which formed the basis of the present Powerhouse Museum's collection. Liversidge also played a major role in establishing the *Australasian Association for the Advancement of Science* which held its first congress in 1888.

This book is essential reading for those interested in the development of science in colonial Australia, particularly the fields of crystallography, mineral chemistry, chemical geology and strategic minerals policy.

To order your copy, please complete the form Liversidge Book Order Form available at: http://royalsoc.org.au/publications/books/McLeod_Liversidge_Order_Form.pdf and return it together with your payment to:

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The Royal Society of New South Wales

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