FIRST DIRECT DETECTION OF GRAVITATIONAL WAVES: AUSTRALIA'S ROLE

AUSTRALIAN TERAHERTZ PHYSICS

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Cover
Still image extracted from a simulation of event GW150914 - the first detection of a binary black hole merger using the Laser Interferometer Gravitational-wave Observatory. This simulation was produced by the Simulating extreme Spacetimes collaboration and falls under the license: http://creativecommons.org/licenses/by-sa/4.0/. This still image was captured at about 20 msec before merger with the black holes’ velocities exceeding half the speed of light at merger. The insert shows the waveform recorded at the LIGO Hanford detector. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualisation the times series (light grey) is filtered with a 35-350 Hz bandpass filter to suppress large fluctuations outside the detector’s most sensitive frequency band, and band reject filters to remove the strong instrumental spectral lines. The thin yellow line just visible centred in the coloured region is a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914. Coloured areas show 90% credible regions for two independent waveform reconstructions, one using binary black hole templates, the other calculates the strain as a linear combination of sine-Gaussian wavelets.
“Big Science” has become a significant component of not only physics research but also other fields. Some of the fundamental discoveries of recent years – the Higgs boson, gravitational waves – would not have been possible without major international investment and scientific collaboration. The first detection of gravitational waves last year involved many Australian physicists from several institutions via the Australian Consortium for Interferometric Gravitational-wave Astronomy (ACIGA). David McClelland gives an account of Australian involvement in his article, *Australia’s role in the first direct detection of gravitational waves*. We discussed whether to include all contributors as authors, but for practical reasons decided to settle on David as author with other contributors acknowledged in an appendix: 56 in addition to David, from 6 institutions. First detections are only the initial step. As David mentions, ACIGA has served its purpose, in effect replaced by Australian Research Council Centre of Excellence in Gravitational-wave Astronomy (OzGrav), which will enable Australian physicists to remain at the forefront of new discoveries using this brand new tool for astronomy. With our ideal southern hemisphere location, the quest for a large-scale Australian third generation Observatory remains firmly in their sight.

Terahertz-frequency electromagnetic radiation occupies a spectral region between optical and microwave frequencies, where sources and detectors are notoriously problematic. There is, however, an active research community in Australia and this is the subject of Roger Lewis’ article, *Australian Terahertz Physics*. As Roger points out, this part of the spectrum has relevance to many fields of science and as it matures we can expect to see more terahertz-based applications.

The third and final article in this issue is concerned with procedures for judging the quality of scientific output and whether they are beneficial or detrimental to good science. Tim Davis in his article, *When “Good business practice” turns “Science” into “Non-science”*, puts forward strong arguments that they are detrimental.

School physics syllabuses are revised from time to time, and are influenced by pedagogical conventions at the time, the social context, and, of course, new exciting discoveries – the Higgs boson and gravitational waves, for example. New South Wales has very recently released a new syllabus for Stage 6 (years 11 & 12) – see News item. The lead-up to finalization of the syllabus involved considerable controversy. There is an opportunity here for a critique of the new syllabus; I would be happy to consider any such submission for publication in a forthcoming issue.

Brian James
AIP 2017 - WELCOME TO A NEW TEAM

One thing I never thought I would say is that the Australian Institute of Physics can learn something from the election of Donald Trump! As the incoming President of the AIP at a time close to one of the most talked about inaugurations in living memory, it is not surprising that colleagues have had fun with suggestions that the first thing the new executive should attend to is building a wall in order to make the AIP great.

But first, as befits a new administration, some background checks. I am delighted to introduce A/Prof Jodie Bradby as our new vice-president. Jodi is in the Research School of Physics and Engineering at the Australian National University where she leads research into physical responses of materials to various forms of mechanical stress. Jodi will be known to AIP members as she was an excellent AIP Women in Physics lecturer in 2015. Also, replacing Joe Hope, who has recently retired from the role, Kirrily Rule will be taking up the challenge of secretary. My thanks to Warrick Couch who is now immediate past president – during Warrick’s term as president we undertook, was relevance and as assessed in the last major survey undertaken, was relevance and “what’s in it for me”.

Addressing these concerns aligns perfectly with the core objectives of the AIP as set out by (dare I say it) our founding fathers. Paraphrasing the AIP constitution, these are to promote and further physics and its applications and maintain and improve the standards of and advocate on behalf of the discipline. Our goal as the executive is to focus on better communications; better structures to help our members do more good physics and applications; and more advocacy to strengthen the discipline. Accordingly, in the coming year you will, through the medium of the AIP monthly bulletin, hear more about the benefits of membership (it is all very well to have good benefits but people need to hear about them as well). We will continue the process of modernisation of the structures of the AIP – including the constitution redraft and the membership process. And we will continue to advocate for improvements to the discipline, including to our gender and diversity policies.

There is a lot to be excited about in physics. We seem to be at the beginning of a flood of new Earth-like planets in the so-called Goldilocks zone, the detection of gravitational waves may provide new insights into the universe, and regular advances in quantum entanglement and manipulation bode well for the future of quantum computation. The AIP exists to foster that excitement, to help create better physicists through networking, education and activities such as accrediting of degree courses, and to work with stakeholders such as governments and employer groups to help foster the discipline. So, no Trump-mandated walls from the AIP this year, but maybe we will indulge in a little more trump-eting of our successes....

Andrew Peele

Andrew Peele
NEWS & COMMENT

ASKAP starts observations
The CSIRO’s ASKAP (Australian Square Kilometre Array Pathfinder) telescope has started making observations. ASKAP consists of 36 identical 12-metre wide dish antennas (12 of which are currently in operation) and is located in Western Australia at the Murchison Radio-astronomy Observatory (MRO), about 315 km northeast of Geraldton.

Several of the The Australian Square Kilometre Array Pathfinder’s telescopes. (Credit: CSIRO)

The first project is one of ASKAP’s largest surveys, WALLABY (Widefield ASKAP L-band Legacy All-sky Blind survey). The survey involves 100-plus scientists from many countries, led by CSIRO astronomer, Bärbel Koribalski, and Lister Staveley-Smith of the International Centre for Radio Astronomy Research (ICRAR), University of Western Australia.

The aim is to detect and measure neutral hydrogen gas in galaxies over three-quarters of the sky. To see the farthest of these galaxies involves looking three billion years back into the universe’s past, with a redshift of 0.26. In the nearby (low-redshift) universe, most of the neutral hydrogen resides in galaxies; so mapping the neutral hydrogen is a useful way to map the galaxies.

ASKAP sees large pieces of sky with a field of view of 30 square degrees. The WALLABY team will observe 1,200 of these fields. Each field contains about 500 galaxies detectable in neutral hydrogen, giving a total of 600,000 galaxies. Simply detecting all the WALLABY galaxies will take more than two years, and interpreting the data even longer. ASKAP’s data will live in a huge archive that astronomers will sift through over many years with the help of supercomputers at the Pawsey Centre in Perth, Western Australia.

(Source: CSIRO and The Conversation)

Award for Outstanding Service to Physics in Australia to Cathy Foley
Cathy Foley, Deputy and Science Director of CSIRO Manufacturing, has received an AIP Award for Outstanding Service to Physics in recognition of her exceptional contributions to physics out of the lab.

Dr Cathy Foley, receiving her award from President Professor Warrick Couch at the APPC-AIP Congress.

Cathy Foley is an award-winning scientist, a driving force behind Australian innovation and science policy, and a passionate advocate and role model for women in science. She has excelled in each of these roles in their own right—and combining the demands of all three is hugely impressive.

She has been honoured both for her research and her distinguished career in science leadership, including serving as the President of the AIP and President of Science and Technology Australia. She is also known for her strong advocacy of women in STEM.

The AIP Award for Outstanding Service to Physics recognises an exceptional contribution on the part of an individual. Nominations may be made by a Branch Committee or by three members of the AIP.
New Defence Innovation Partnership
Minister for Defence Industry, the Hon Christopher Pyne MP, recently announced the establishment of the Defence Innovation Partnership between the Defence Science and Technology (DST) Group and South Australian Universities. According to the Minister, “this new partnership will enable Defence to further leverage science and technology expertise from South Australia’s leading academic institutions and industry.”

The initiative follows the opening last year of the Centre for Defence Industry Capability, based in South Australia. The Centre includes an innovation hub intended to assist small and medium enterprises with innovative ideas to contribute to our defence capability.

Launch of Defence Innovation Partnership SA. (credit: DST Group)

This new partnership between the DST Group and the South Australian university sector aims to create a centre for future defence related research networks in South Australia, and provide a platform for industry and universities in South Australia that will enable joint cross-disciplinary research to help solve Defence’s technology challenges. As the coordinator and innovation integrator of Defence’s research and development activities, DST Group would be a key player in the partnership, contributing up to $150,000 per year for research projects as well as seconding a senior researcher.

The initiative is consistent with the 2016 White Paper, which called for greater alignment across the defence innovation sector through closer cooperation with industry and academia. A similar initiative has already been implemented in Victoria, and discussions with other interested states are underway.

New neutron reflectometer for ANSTO
ANSTO negotiated the transfer of the neutron reflectometer from the BER-II Research Reactor at Helmholtz-Zentrum Berlin (HZB) in 2015 and renewed a MOU for scientific collaboration with the German research organisation in 2016.

The instrument, which arrived at ANSTO recently, will be located in the Neutron Guide Hall, adjacent to the BILBY instrument at the Australian Centre for Neutron Scattering (ACNS).

The reflectometer, formerly known as BioRef, has been given a new name, SPATZ (the German word for sparrow). This is in keeping with the tradition of naming other instruments at ACNS after Australian and other fauna.

Rendering of the SPATZ neutron reflectometer (credit: ANSTO).

The real power of this instrument is its ability to use a whole new range of sample environments that cannot currently be used on the existing reflectometer, PLATYPUS, thus expanding the ACNS capabilities in studying surfaces and interfaces. It employs a high-flux cold-neutron source and can be used for a wide range of applications in biomedicine, energy, and materials science. It becomes the fifteenth neutron-beam instrument operated by the ACNS at ANSTO.

The project is being supervised by Instrument Scientist, Dr Anton LeBrun, and Instrument Engineer, Stewart Pullen.

New NSW HSC Physics syllabus
A new Physics syllabus for the NSW Higher School Certificate (stage 6: years 11 & 12) has been released. The syllabus includes the following rationale.
edness of seemingly dissimilar phenomena. Students who study physics are encouraged to use observations to develop quantitative models of real world problems and derive relationships between variables. They are required to engage in solving equations based on these models, make predictions, and analyse the interconnectedness of physical entities. The Physics course builds on students' knowledge and skills developed in the Science Stage 5 course and helps them develop a greater understanding of physics as a foundation for undertaking post-school studies in a wide range of Science, Technology, Engineering and Mathematics (STEM) fields. A knowledge and understanding of physics often provides the unifying link between interdisciplinary studies. The study of physics provides the foundation knowledge and skills required to support participation in a range of careers. It is a discipline that utilises innovative and creative thinking to address new challenges, such as sustainability, energy efficiency and the creation of new materials.


New Executive, 2017-9

The new executive (2017-9) was elected at the AIP Council meeting in Melbourne, 2 February. The members of the executive are:

President: Andrew Peele
(Australian Synchrotron)

Vice President: Jodie Bradby
(ANU)

Honorary Secretary: Kirrily Rule
(ANSTO)

Honorary Treasurer: Judith Pollard
(Univ Adelaide)

Honorary Registrar: Ian McArthur
(UWA)

Immediate Past President: Warrick Couch
(AAO)

Special Project Officer: Olivia Samardzic
(DST Group)
Australia’s role in the first direct detection of gravitational waves

D.E. McClelland¹
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The detection of gravitational waves by the Laser Interferometer Gravitational Observatory has opened a new sense with which to observe the Universe. Australia is a partner in this observatory, led by the USA with the UK and Germany. In this article we summarise the contributions of Australian scientists to this momentous discovery.

Gravitational-Wave Detection
On September 14, 2015, the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) detectors recorded the first direct observation of gravitational waves (GWs) [1], see Figure 1. The signal from event GW150914 was shown to have been generated some 1.3 billion years ago, during the inspiral and merger of two black holes (35 and 30 solar mass respectively) to form a single 62 solar mass black hole [2]. This observation confirmed one of the most important theories in physics, Einstein’s theory of general relativity, in the nonlinear strong gravity limit. It confirmed that GWs propagate over astrophysical distances and can be detected by the modulation imposed on the optical path of a suspended mirror laser interferometer. We now have a second form of radiation (in addition to electromagnetic) with which to study the Universe. The first detection was from a never before seen coalescing black hole binary system made up of pure space time curvature with no identifiable electromagnetic (EM) radiation [1]. This is likely to be only the first discovery of events invisible in the EM spectrum.

The aLIGO detectors are giant opto-mechanical sensors that explore the audio spectrum from 10 Hz to 2 kHz [3], see Figure 2. The local effect of a gravitational wave is a time varying change in the space-time metric: the compressing and stretching of space-time itself.

![Figure 1: The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. For visualization, all time series are filtered with a 35–350 Hz band-pass filter. Top row, left: H1 strain. Top row, right: L1 strain. GW150914 arrived first at L1 and 6.9±0.5 ms later at H1; for a visual comparison the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors’ relative orientations). Bottom row: A time-frequency representation of the strain data, showing the signal frequency increasing over time (the ‘chirp’).](image-url)
But space-time is very stiff: even though in energy terms, a binary black hole merger can briefly outshine the EM radiation of the entire universe, the resulting ‘ripples in the fabric of space-time’ (expressed as a relative length change, $\delta L/L$) are extremely small, and upon arriving at the Earth of the order of $10^{-21}$ to $10^{-23}$, equivalent to changing the Earth-Sun distance by a picometer.

The LIGO frequency band is expected to contain signals from dynamical astrophysical processes of great interest, such as the inspiral and merger of compact objects (solar- and intermediate-mass black holes, neutron stars, and neutron star-black hole systems), stellar core-collapse supernovae, spinning neutron stars and various astrophysical backgrounds. Even more tantalising are the totally unpredicted sources.

Building a detector of such sensitivity is an extremely demanding task. Einstein thought it impossible. It took the invention of the laser, transistor, revolutions in optics and materials and the development of quantum optics, before it could even really become a possibility.

The aLIGO detectors are improved sensors placed at the two existing LIGO Observatories. The optical layout is depicted in Figure 3. The test mass mirrors are hung from sophisticated suspensions systems so that, above resonance frequencies, they are effectively free to move. Being quadrupolar radiation, a passing GW will alternately stretch then contract one arm of a Michelson interferometer whilst contracting then stretching the other arm. The arm cavities magnify the phase change imposed on the light. Interfering the single frequency light beams from the two arms at the beamsplitter cancels common noise whilst the signal adds. The power and signal mirrors further increase sensitivity and optimise response [4].

Three basic noise sources limit interferometer sensitivity: thermal, quantum, and Newtonian (gravity gradient) noise. Thermal noise [5] arises from thermally driven atomic fluctuations that lead to random Brownian motion of the test masses, their highly reflective mirror coatings and their suspensions. Quantum noise [6] arises from quantum fluctuation in the amplitude and phase of a light field sensing the mirror separations. Newtonian noise arises from the direct gravitational forces exerted on the interferometer mirrors by nearby changing mass distributions, primarily caused by density fluctuations of the surrounding earth due to seismic waves as well as low frequency atmospheric density changes [7]. Building an interferometer limited by these basic processes requires the elimination of a myriad of technical noises, such as laser frequency and intensity noise, acoustic noise, refractive index perturbations and seismic noise. Even then the majority of signals will still lie buried in noise.

It took the efforts of more than a thousand scientists, engineers, technicians and students to finally achieve the ‘impossible’. Instrument scientists and engineers designed and built the instrument – the lasers, optics, isolation and suspension systems, electronics, control systems, vacuum systems, and readout systems to produce the data channel. Then teams of detector charac-
terisation experts pored over thousands of monitoring channels data looking for, understanding and eliminating artifacts and calibrating the instruments to produce ‘clean’ data. Data analysts then used pipelines and template banks they had developed to look for GW signals lurking within that data. Australian researchers made key contributions across all areas.

The Australian Gravitational Wave Detection Effort

In 1995, McClelland’s quantum noise group (ANU), Munch’s optics group (U Adelaide) and Blair’s GW group (UWA) formed the Australian Consortium for Interferometric Gravitational-wave Astronomy (ACIGA), with John Sandeman as its inaugural Chairperson. ACIGA [8] was initially formulated to grow R&D on laser interferometry and to advocate for the construction of a gravitational wave detector in Australia. The instrument science programs expanded with the addition of key researchers such as Shaddock, Slagmolen and Ward (ANU), Ju and Zhao (UWA) and Veitch and Ottaway (Adelaide). Data analysis programs were added at ANU (Scott) in 1998 and at UWA (Wen). Later the University of Melbourne (Melatos), Monash University (Levin and Thrane) and Charles Sturt University (Charlton) joined ACIGA. The CSIRO’s Centre for Precision Optics joined as an associate member. ACIGA was a founding member of the LIGO Scientific Collaboration when it formed in 1998.

By 2007, the initial LIGO project reached (and later exceeded) its design sensitivity. ACIGA partners made major contributions, from understanding and modelling thermal noise [9], to polishing core optics, global control strategies [11], detector characterisation [12], and quantum noise reduction [13]. We built vital software components for the LIGO Data Analysis System and data analysis strategies [14,15,16]. Successful commissioning of initial LIGO resulted in the US National Science Foundation in 2008 funding the construction of a

Figure 4: Clockwise from top left. Current ACIGA Chair Bram Slagmolen installing the suspension sensors and actuators at LIGO Hanford Observatory. ACIGA celebrates announcement of the detection of gravitational waves. Rob Ward commissioning lock acquisition at the LIGO Livingston Observatory from the control room. Tip-Tilt small optics suspensions being installed at LLO. Adjusting the telescope for the arm length stabilisation system inside the end-station at LIGO Hanford Observatory.
second-generation detector that was expected to reach a sensitivity at which GWs would be detected. aLIGO was co-funded by the United Kingdom and Germany. In 2009, funded by the Australian Research Council [17], Australia became the 4th member country of the Advanced LIGO Project, and was destined to be a major contributor to the first direct detection. These contributions are summarised below.

Interferometer Modelling
ACIGA researchers developed a general method for computing thermal noise in gravitational-wave interferometers. This method is now the standard tool in the field [9,18] leading to the prediction that the mirror coatings would be a serious source of noise in aLIGO. We participated in developing theoretical tools for analysis of the interferometer’s quantum behaviour, thus laying the foundation for studies of a very important quantum noise in LIGO [19], and contributed to the modelling and design of the length control system adapted for aLIGO [11]. We also played a major role in the modelling of parametric instabilities (see later).

One of the most challenging problems in operating complex, suspended interferometers like Advanced LIGO is lock acquisition, which is the complex start-up process which is necessary for gravitational wave detectors to function. It is not a matter of better performance, but of whether the detector can operate at all. To aid in the lock acquisition, we contributed a critical piece of hardware, called the Arm Length Stabilisation system [21], which comprises a second set of auxiliary laser beams (at 532 nm, see Figure 4), photodetectors, and phase locking systems dedicated to the lock acquisition process. After prototyping [21], Australian researchers worked with onsite staff to install and commission this system on the LIGO interferometers, culminating in the first lock being achieved in May 2014 [22], with the first automated lock shortly thereafter in June 2014.

The test mass mirrors in Advanced LIGO are nearly perfect surfaces and have very low optical absorption. Nonetheless, the high circulating laser power in the interferometer, coupled with any amount of absorption, can cause intolerable levels of thermal distortion of the mirrors. To counter this, we developed, constructed, installed and commissioned, a set of ultra-high precision Hartmann wavefront sensors that can measure these distortions, and can do so when the distorted mirrors are buried deep within the LIGO vacuum envelope [23,24,25]. This information is then used to drive an adaptive optics system within the interferometer, thus compensating for the effect of the distortion.

Building on the work of Braginsky, Strygin, and Vyatchanin [26], we performed detailed computations that showed that in the resonant cavities of aLIGO, parametric instabilities would be extremely difficult to avoid without the mitigation strategies in place [27]. These three-mode opto-mechanical processes couple energy from the laser field into the acoustic modes of the mirrors leading to loss of lock if left untamed. They have the potential to limit the sensitivity of Advanced LIGO, or mirrors, see Figure 4, for routing the signal laser beam around inside the detector vacuum system [20]. These mirrors directed the gravitational wave signal-imprinted laser beam to the photodetectors where the signal was recorded, preserving the low-noise characteristics of the beam. ACIGA affiliate, the CSIRO Centre for Precision Optics, coated under contract key optics in aLIGO including the power and signal recycling mirrors and the main beam-splitter, see Figure 5.

Figure 5: CSIRO Researchers coating aLIGO optics

Hardware and Instrumentation
ACIGA contributed a significant amount of critical hardware to Advanced LIGO. We designed, built, installed, and commissioned 30 suspended optic steering mirrors, see Figure 4, for routing the signal laser beam around inside the detector vacuum system [20]. These mirrors directed the gravitational wave signal-imprinted laser beam to the photodetectors where the signal was recorded, preserving the low-noise characteristics of the beam. ACIGA affiliate, the CSIRO Centre for Precision Optics, coated under contract key optics in aLIGO including the power and signal recycling mirrors and the main beam-splitter, see Figure 5.
even prevent it from operating. We carried out an extensive investigation of parametric instabilities [28], many years before they were first seen in Advanced LIGO [29] and led the development of mitigation strategies [30]. We first observed such a parametric instability and investigated suppression techniques at our high optical power test facility at Gingin, Figure 6. Thanks to this Australian driven research, when the instabilities were first encountered in Advanced LIGO, solutions were ready to be deployed [29].

![Figure 6: Gingin precinct W.A. showing the high optical power test facility at the top. The Zadko telescope features in the middle left, with the award winning Gravity Discovery Centre at the bottom of the picture.](image)

Working with a team of international researchers ACIGA researchers developed the hardware injection system that was used to vet the first detections of gravitational waves [31]. The hardware injection system actuates on the LIGO test masses in order to simulate gravitational-wave signals. By checking that the measured signal is consistent with the injected signal, researchers are able to conduct an end-to-end test of the instrument and analysis pipelines.

**Detector Characterisation**

In detector characterisation, we led efforts to study, characterise, and mitigate the effects of correlated noise from geophysical phenomena such as Schumann resonances [32-34]. This work helps ensure that LIGO sensitivity is not adversely affected by the environment. It ensures that LIGO does not observe a false positive signal from geophysical effects. ACIGA researchers undertook data quality shifts looking for abnormalities and transient noise (glitches) which could pollute the data. Through the LIGO Fellows program we had scientists at site during Advanced LIGO observing runs. Our PhD students Ellie King and Carl Blair were fortunate enough to be at LIGO sites when first detection was recorded.

**Data Analysis**

In data analysis, ACIGA researchers’ contributions to Advanced LIGO have concentrated mainly on developing data analysis pipelines for astrophysically important sources in the Advanced Detector Era. We developed a real-time low-latency pipeline (program), using a new filtering method called summed parallel infinite impulse response (SPIIR) method, see Figure 7, to search for GWs from compact binary systems in sub-minute latency. This pipeline was later extended to search for a larger range of binary systems including high-mass, and was used to verify the initial detections [35-39].

![Figure 7: Detection of event GW150914 by ACIGA’s SPIIR pipeline.](image)

We developed pipelines targeting continuous-wave sources like isolated and accreting neutron stars, which emit persistent, quasi-monochromatic signals [40,41] and non-pulsing neutron stars [42]. These algorithms are currently running on data from aLIGO’s first observing run. More recently we developed a new algorithm searching for continuous-wave signals from low-mass X-ray binaries whose frequencies are unknown and wander stochastically [43].

We also have long contributed to the search for stochastic backgrounds [44]. Following GW150914, ACIGA
led an effort to map the distribution of gravitational-wave power on the sky [45]. We have also played an important role in the development of search algorithms used in other gravitational-wave data analyses, e.g. [46-49].

ACIGA researchers featured in electromagnetic follow-up of LIGO’s first detections, with facilities such as using the Gravitational-Wave Optical Transient Observer (GOTO), ZADKO, Skymapper, and the Murchison Widefield Array.

Summary
During the 22 years since its formation, ACIGA provided the vehicle to harness and organise gravitational wave research in Australia. Our contributions earned us partnership in one of the greatest achievements in physics. This achievement has been recognised through the awarding of the 2017 AAS Bruno Rossi Prize, 2016 Gruber Cosmology Prize and the 2016 Special Breakthrough Prize in Fundamental Physics to the authors of the detection paper, including 43 researchers at Australian institutions. In this article we summarised our direct contributions to Advanced LIGO’s first observing run and initial detections of gravitational waves. We have not discussed the large amount of work we are doing on astrophysical interpretation [50-54], network analyses [55-56] and instrument development for detector upgrades [57-59]. ACIGA served its purpose. Now, the Australian Research Council Centre of Excellence in Gravitational-wave Discovery (OzGrav) will enable us to be at the forefront of new discoveries using this brand-new tool for astronomy whilst developing future generations of detectors. With our ideal southern hemisphere location, the quest for a large-scale Australian third generation Observatory remains firmly in our sight.

Acknowledgements
We acknowledge the enormous contributions of our colleagues and friends in the LIGO Scientific Collaboration and the Virgo Collaboration. We thank the Australian Research Council and our universities for ongoing support over many years and acknowledge the foresight and investment of the US National Science Foundation, the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany. DM would like to acknowledge the support and mentorship of Professors John Sandeman and Hans Bachor, both of whom played crucial roles in the early days of interferometric detection of gravitational waves in Australia.

References
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Author Biography

David McClelland seeded the field of interferometric detection of gravitational waves in Australia when in 1989 he contacted David Blair with a proposal to combine UWA’s expertise in vibration isolation and mechanical systems with ANU’s expertise in quantum limited precision optical measurement. He became the second Chairperson of ACIGA in 1998 leading the consortium into the LIGO Scientific Collaboration as a founding member in that year and then in 2009 into full partnership in Advanced LIGO. Currently he is a professor at the Australian National University in the Research School of Physics and Engineering, Director of the ANU’s Centre for Gravitational Physics and Deputy Director of OzGrav - the Australian Research Council Centre of Excellence in Gravitational-wave Discovery.
Australian Terahertz Physics

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Terahertz-frequency electromagnetic radiation falls between the microwave and visible regions of the electromagnetic spectrum, in other words, between electronics and photonics, a region historically difficult to access and relatively lacking in sources and detectors, so sometimes called ‘the terahertz gap’. Australian researchers have been active in this field since its emergence and are currently riding a ‘terahertz wave’, as evidenced by such indicators of research intensity as publications, grants and higher degree research students. The scope of activity ranges from fundamental research in condensed matter physics to applications in laser manufacturing and biomedicine.

1. Introduction

The word ‘terahertz’ derives from the Greek word ‘teras’, meaning monster, and the German physicist Heinrich Hertz, after whom the SI unit of frequency is named. Thus ‘terahertz’ conveys a monstrously huge frequency. More precisely, it is one million million oscillations per second. The frequency unit, written as 1 THz, is thus exactly $10^{12}$ Hz. More loosely, the term ‘terahertz’ has come to refer to the frequency range spanning a decade above and below this point, that is, 0.1 to 10 THz; thus we might write ‘terahertz ~ $10^{12±1}$ Hz’.

While terahertz frequencies may refer to mechanical phenomenon, they are usually associated with electromagnetic phenomenon. A photon of frequency 1 THz has energy of about 4.14 meV and vacuum wavelength of about 300 µm. (Spectroscopists might prefer 33.4 cm$^{-1}$). The relations between photon frequency, energy, vacuum wavenumber and vacuum wavelength in this region are depicted in Figure 1. In the electromagnetic spectrum, this falls between the radio or microwave region at lower frequencies and the visible region at higher frequencies. Thus the terahertz region is said to lie between electronics and photonics.

In view of the relative scarcity of sources, detectors and components in this region of the electromagnetic spectrum, the term ‘terahertz gap’ has achieved some traction. The terahertz region can be described as the richest, but least explored, in the electromagnetic spectrum [1].

2. Frequency Is Fundamental

The THz is a unit of frequency. In the SI system, this is defined in terms of the base unit of time. Yet, arguably, frequency is more fundamental than time.

Within the SI system, the second is defined in terms of transitions between levels of the Cs atom. It seems more natural to speak of the frequency of this oscillation rather than the period.

To measure time requires an instrument, a clock. To measure frequency is simpler. It requires only a starting and finishing point and the ability to count. The measurement of frequency is made more accurate by increasing the distance between the starting and the finishing point.

Given these principles, perhaps it is time to consider replacing the SI base unit of time with a base unit of frequency.

From a pedagogical point of view, there are reasons to prefer the unit of THz over the more common unit of nm when discussing optical phenomena. For a start, the frequency is preserved when a photon travels from one medium to another, whereas the wavelength is not. Secondly, the frequency is directly proportional to the energy, the constant of proportionality being Planck’s
constant. (In a deep sense, frequency and energy are different words for the same thing.) Thus physics problems involving the Bohr atom, the photoelectric effect, and so on, are much clearer and cleaner when THz, rather than nm, are used. It is not hard to get used to THz. Red is 400 THz, blue is 800 THz, the He-Ne laser is 474 THz, the Na-D line 509 THz [2].

3. A Brief History

Searching the Scopus database for documents that contain either ‘terahertz’ or ‘thz’ in the title, abstract or keywords, and ‘Australia’ in the affiliation, yielded 956 documents [3]. The earliest of these dates to 1972 and concerns monitoring the NSL standard of EMF using the AC Josephson effect [4]. Other documents dating from the 80s involve determination of the volt, $2e/h$ and $h/e^2$ in SI units [5, 6]. Thus, THz frequencies have been closely associated with metrology for almost half a century.

The other early Australian terahertz documents concern fundamental excitations in condensed matter, such as magnons [7, 8, 9] and phonons [10]. The first papers we would associate with terahertz physics as the term is used today appeared in 1995 and concerned acoustic phonons [11, 12, 13, 14]. The field has grown rapidly, and Australia is currently producing about a hundred papers a year – 2013: 90; 2014: 99; 2015: 90.

4. Terahertz Phenomena

Magnons and phonons are examples of fundamental excitations that have characteristic frequencies. Many other fundamental excitations occur at terahertz frequencies. The full zoo ranges from simple photons, phonons and plasmons, to such combinations as polaritons, polarons, magneto-polarons and even magneto-photo-phonon resonances [15]. Spatial confinement in semiconductor heterostructures often leads to energy spacings, and so to transitions, in the terahertz regime. Introducing a magnetic field produces further terahertz phenomena, such as the Zeeman effect (for bound charge carriers) and cyclotron resonance (for free carriers). Recently, there has been much interest in metamaterials at terahertz frequencies.

The range of topics of research may be illustrated by a sampling of the 27 ARC Discovery Grants that have been awarded in the area since 2004. Topics include non-linear physics (DP0452713, Chao Zhang); metamaterials (DP1095151, Withawat Withayachumnankul; DP120103942, Boris Kuhlmey); biomedical imaging (DP1096514, Vincent Wallace); terahertz generation (DP110103748, Andrew Lee); quantum cascade lasers (DP160103910, Aleksandar Rakic). Further details of these and the other ARC grants are available at the ARC website [16]. A summary of the support received across various ARC schemes is given in Figure 2. The total of about $20M – amounting to less than $1 per person in Australia – has been very effectively invested.

5. Equipment And Infrastructure

The development of experimental terahertz methods over the last seventy years is summarised in Figure 3 (based on a diagram of Prof. Kiyomi Sakai and reproduced and extended with his kind permission). Sources are shown in mustard, detectors in yellow, technologies in dark green and breakthroughs in blue. Australian researchers are well-equipped across this timeline, from Golay cells to Quantum Cascade Lasers.
The establishment and maintenance of state-of-the-art terahertz infrastructure in Australia has been facilitated by seven Australian Research Council (ARC) Linkage Infrastructure, Equipment and Facilities (LIEF) Grants. Starting in 2004, a time-domain system was set up at the University of Wollongong (UOW; LE0453974). A more comprehensive system was then established at the University of Adelaide (UA; LE0560716), followed by a two-colour continuous wave system at UOW (LE0668322). More recently, next-generation time-domain systems have been provided to RMIT (LE150100001), University of Western Australia (UWA; LE150100078), University of New South Wales (UNSW, LE160100107) and UOW (LE170100020). Nowadays, terahertz systems are being seen less as an exotic curiosity but rather as a fundamental tool in condensed matter and materials research.

It is worth mentioning that the two largest pieces of scientific infrastructure in the country, the nuclear reactor and the synchrotron, are terahertz-related. As the early work on magnons illustrates, neutrons of appropriate energy probe the same phenomena in solids as terahertz-frequency photons. The synchrotron, among other frequencies, generates terahertz-frequency photons, and a dedicated beam line optimizes their use.

6. Publications
The infrastructure and working support has resulted in many successful outcomes, as evidenced by the 956 publications on the Scopus database involving ‘terahertz or thz’ in the keyword, abstract or title and ‘Australia’ in the affiliation. These have appeared in high-impact journals, such as Nature Communications, Nature Materials, Nature Photonics, Physical Review Letters, Physical Review B, Optics Express, and Optics Letters. The most-cited article [17], with more than 1500 citations, is fifth on the world-wide list of top-cited terahertz publications. With respect to the world-wide output of 46,773 documents, the Australian contribution is 2.0%. This is similar to, but slightly higher than, the 1.7% when ‘physics’ is used in the search rather than ‘terahertz’. Thus Australian terahertz workers are at least holding their own, or even punching above their weight, on the world stage.

7. Theses
A total of 45 theses involving terahertz are available in the national repository [18]. From one in 2003 and one in 2004, the rate has picked up and is now running at about ten per year. Various of these graduates have gone on to DECRAs and positions in Australian and overseas universities.

8. International Linkages
Now let us consider further Australian Terahertz Physics in the broader context of the global effort. Specific support was given to establishing international linkages under the (now defunct) ARC Linkage International Grants scheme. These were in 2002 (LX0231874), 2006 (LX0668576) and 2007 (LX0776043).

The two specialist international journals in the field have editorial board members from Australia. Vince Wallace (UWA) serves on the board of the IEEE Transactions on Terahertz Science and Technology. Roger Lewis (UOW) serves on the board of the Journal Of Infrared, Millimeter And Terahertz Waves.

The top-tier international body, the International Society of Infrared, Millimeter and Terahertz Waves has had continuous Australian representation for decades via Trevor Bird (CSIRO), followed by Chao Zhang (UOW, 2010-2016) and now Roger Lewis (2017-2023).

9. Engagement and Impact
The current federal government is advocating innovation for economic benefit and is interested in assessing the engagement and impact of research. Australian Terahertz Physics is already linking up with end-users in taking fundamental research results to practical applications. This is exemplified by projects supported by the ARC Linkage Project scheme. UWA and Macquarie are leading the way here. LP110100728 (UWA) concerned skin burns, LP140100344 (Macquarie) electronic packaging, LP140100724 developing better THz lasers and LP160100325 biomedicine. It is expected, as the field continues to mature, more and more terahertz-based inventions will find their way from the laboratory to the marketplace.

10. Conclusion
From the reactor to the synchrotron, in university labs around the country, and in more and more local industries, Australian Terahertz Physics is burgeoning.
References


Author Biography

Roger Lewis is an active researcher in the area of terahertz science and technology. He is a Fellow of the Australian Institute of Physics and a Fellow of the Royal Microscopical Society. He is also an accomplished teacher, as recognised by a Vice-Chancellor’s Award for Outstanding Contribution to Teaching and Learning, The NSW Minister for Education and Training & The Australian College of Educators Quality Teaching Award, and a Carrick Citation. Lewis is also active in academic governance. He was Head of the School of Physics at the University of Wollongong 2002-2007 and currently serves as the Associate Dean Research in the Faculty of Engineering and Information Sciences.

Award for Outstanding Service to Physics in Australia

This Award will be open to members of the AIP. Nominations may be made by a Branch Committee or by three members of the AIP. There will be no more than three awards nationwide in any one year and the Selection Committee, which will be appointed by the Executive, will reserve the right to make no awards in any one year.

The AIP Award for Outstanding Service to Physics will recognise an exceptional contribution on the part of an individual. Nominations should be accompanied by a clear one or two page citation describing the outstanding service given by the nominee.

The closing date for nominations is 1 June 2017. For further information see the AIP website or the AIP Special Projects Officer, Olivia Samandzic: aip_member_one@aip.org.au.
When “Good business practice” turns “Science” into “Non-science”

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“Good business practice” is to judge a scientist’s work performance based on numbers - the key performance indicators (KPIs) - that supposedly measure the effectiveness of the research and the person or groups conducting it. Typical KPIs for scientists are the numbers of citations, the H-indexes, the impact factors of the journals in which they publish, the number of collaborations and the dollar value of grants received. Ensuring these numbers are big is important for success. But is this really good for science? Does it drive us to produce better and more useful science outcomes? Or does it do the opposite and convert science into nonsense?

On ABC radio national in 2009 there was a Background Briefing on the rise of the professional manager and what it meant for business. The discussion centred on the concept of obtaining a degree in management so you could manage anything, irrespective of your knowledge about the company or business. It was from Frederick W. Taylor, the inventor of the time and motion study and the founder of Scientific Management theory, that “the business schools derived their obsession with numbers and measurement… It’s also due to Taylor’s influence that the emphasis in business shifted from people to figures, and from quality to quantity. We started to hear talk about the bottom line, employees started to be called human resources, and we saw the rise of the influence of the accountant. If you don’t possess ‘domain knowledge’, how do you run a company? Well, you do it through the accounting department … the characteristic of the new age of management as a profession, is improving the numbers, not improving the product.” [1]

In science we are not isolated from this management culture, which as far as I remember began to infect government research labs in Australia around the year 2000 and the universities about 5 years later. The issue centres on how you judge the quality and value of the science being produced and whether or not the scientist is effective in doing his or her job. Rather than assessing ability, potential and outcomes, “good business practice” is to make a judgement based on numbers - the key performance indicators (KPIs) - that supposedly measure the effectiveness of the research and the person or groups conducting it. Typical KPIs for scientists are the numbers of citations, the H-indexes, the impact factors of the journals in which they publish, the number of collaborations and the dollar value of grants received. Ensuring these numbers are big is important for securing a permanent position in science and continued funding for research. So the drive is for “improving the numbers” and not necessarily “improving the product.”

Is this good for science? Does it drive good science?

Consider two related performance indicators - the number of citations and the impact factor of the journal. Most of us will recognise the strong drive to publish in high profile journals like Science or Nature. These “vanity” journals pride themselves on having very high impact factors (a measure of the yearly number of citations per article) but more than this, the editors select those manuscripts they believe will be highly cited. This does a number of things. It favours research groups who already have high numbers of citations and it drives researchers to market their research to appear new and innovative. Scientific details no longer appear in the articles but are relegated to “Supplementary material” where they don’t interfere with a good story. These journals behave like businesses and seem to me to have little interest in serving the scientific community and the general public, particularly if it impacts negatively on their sales or reputation.

The push to increase these numbers is not good for science. Apart from a dramatic increase in the number of scientific papers published (many of which I think are largely irrelevant), it also drives poor science. An example is work published a few years ago in Science [2]. The researchers describe an optical device made from a periodic structure, with a period of \( p = 11 \) mi-
crons, illuminated at normal incidence with infrared radiation of wavelength $\lambda = 8$ microns. A representation of it is shown in Figure 1. Most physics undergraduates would recognise this as a diffraction grating with diffracted orders given by the grating equation:

$$\sin \theta_d = \sin \theta_1 + n\lambda/p.$$ 

The angle of diffraction of the $n = -1$ order is then simply $\theta_d = \sin \theta_1 - \lambda/p$. For the conditions of the experiment the diffraction angle is -46.7 degrees - a simple calculation. Not surprisingly, being a diffraction grating, the angle of the $n = 0$ order beam satisfies Snell’s law of refraction but the angle of the $n = -1$ diffracted beam does not. There is that extra $\lambda/p$ term. However, if you ignore the fact the structure is diffracting, you can pretend that the diffraction equation is actually a generalisation of Snell’s law with an extra phase term $\lambda/p$. And this is what was published in Science, including the condition for the diffraction angle as I have written it, with the diffraction equation renamed as “the Generalised Refraction equation”. The $n = 0$ diffracted order was referred to as “ordinary refraction” and the $n = -1$ diffracted order was renamed “anomalous refraction”.

![Diagram of blazed diffraction grating](image)

**Figure 1: An optical structure with a periodic profile, recently shown to demonstrate “Generalised Refraction”, but more commonly known as a diffraction grating.**

The journal article was a little more cunningly worked than this. The authors created a phase gradient over the grating period to suppress the +1 diffracted order and push most of the optical energy into the -1 diffracted order. This method has been known in optics for over one hundred years and the device is called a blazed diffraction grating, the idea of which was mentioned by Lord Rayleigh in 1874 [3] and demonstrated by Wood in 1910 [4]. The phase profile can be produced in a number of ways, such as by creating a refractive index variation over the surface or cutting the grating rulings at an angle or by generating a phase shift in the gelatine of a photographically imaged grating, as Lord Rayleigh discusses [3]. If you have ever used a commercial spectrometer, then you have probably also used a blazed diffraction grating. For a more recent analysis of blazed phase gratings, including the configuration in reference [2], consult Magnusson’s and Gaylord’s paper from 1978 [5]. Needless to say, none of these works, nor the many others on this topic, were referenced in the Science paper.

The question we must ask then is how did this work ever get published in such as prestigious journal as Science? By all measures this is a very successful paper - at last look it had over 1100 citations and, by itself, would give the journal an impact factor of over 180! Thomson-Reuters places this work in the top 1% of its field based on a highly cited threshold for the publication year. On the basis of these numbers, the science, or non-science, is irrelevant. It is a very successful piece of work ranked at the forefront of physics research. There is no incentive for the editors to admit that indeed all this science is well known and has been for over 140 years.

Another example is a paper purporting to be the plasmonic analogue of Cherenkov Radiation, published in Nature Nanotechnology [6]. In this work the authors “generate surface plasmon wakes, a two-dimensional analogue of Cherenkov radiation.” When I studied physics, which I admit was a long time ago, we were told Cherenkov radiation arose from a charged particle entering a dielectric at a speed greater than the phase velocity of light in that medium [7]. The static electric field associated with the particle, moving within the medium, creates an electromagnetic shock wave propagating at an angle and with a broad distribution of frequencies. The spectral intensity is proportional to frequency so that high frequencies are enhanced, leading to the characteristic blue glow associated with nuclear reactors.

So how well does the plasmonic analogue represent Cherenkov radiation? Let us compare the properties:

Does it involve or imitate a fast moving particle? No.

Is there a constant electric field moving faster than the speed of light in that medium? No.

Does it show a shock wave pulse? No.

Does it show a conversion to a broad frequency spectrum? No.
Figure 2: a) Diagram showing the physics of refraction - a wave incident on an interface produces a sinusoidal excitation profile. The transmitted beam must have a phase that matches this profile. b) Plasmon waves excited on a metal film by light incident out of plane onto a groove in the film. The incident wave produces a phase profile that must be matched by the plasmons, resulting in the equivalent of refraction. The plasmon waves are excited on both sides of the groove.

In fact, the analogue involves a monochromatic and continuous light wave incident on a boundary that generates a continuous surface plasmon wave at the same frequency, propagating at an angle across the surface. One can show (Figure 2) this is the same mechanism as refraction. The only twist is a mirror image to create two waves propagating at angles. The researchers used a thin gold film and a groove to excite the plasmons. So given that the experiment fails to demonstrate almost every characteristic of Cherenkov radiation, why mention Cherenkov radiation at all? Well, the reason is obvious - a simple gold film with a groove showing plasmon refraction would not make it in a Nature journal, but by clever marketing the same piece of research appears more important and impactful, irrespective of the truth of the science.

Of course, I am not the first person to make such criticisms about the practises of high profile science journals and some of the researchers who publish in them. Randy Schekman, a biologist from the USA who won the 2013 Nobel Prize for Medicine was critical of such journals. To quote extracts from an article in the Guardian newspaper [8]:

…pressure to publish in "luxury" journals encouraged researchers to cut corners and pursue trendy fields of science instead of doing more important work. The problem was exacerbated… by editors who were not active scientists but professionals who favoured studies that were likely to make a splash…. A journal’s impact factor is a measure of how often its papers are cited, and is used as a proxy for quality. But Schekman said it was “toxic influence” on science that “introduced a distortion”. He writes: “A paper can become highly cited because it is good science - or because it is eye-catching, provocative, or wrong.”

Adherence to such metrics have a specially detrimental effect on young scientists, who don't have many citations, who don't have high H-indexes or haven't published in high profile journals. Many are highly creative and motivated but have great difficulty in obtaining employment, let alone research funding. A bright postdoc who once worked for me made the astute observation that a really good scientist whose work is way ahead of everyone else in the field will be judged a failure. Being so far in front will mean that few researchers, if any, will cite their papers - their citation rates will be low and therefore they will fail on the metrics. Likewise a scientist who is doing important work but is not at the forefront of a popular research field will not get many citations and will not be able to publish in the high profile journals - another failure. Which leaves the “successful scientists” as those that “ride the crest of the wave”, that publish in the fashionable scientific fields and keep moving to new ones as the fashion shifts and changes, just as Schekman points out. Given that much of science research is publicly funded, this behaviour is not in the public interest and directs funding from potentially more important work. In my view this is a betrayal of the trust that the public places on scientists.

So what are we as a science community to do about this? The push to play the citation game comes from our managers - the senior people in universities, the executives of CSIRO, the people who are in charge of funding, even members of the government itself and, dare I say it, the “successful” senior people in the AIP. As a start we need to ensure the integrity of science and to speak out about the poor behaviours of those who undermine it in the pursuit of improved metrics. Also we can develop our own criteria as to what constitutes valuable scientific research and encourage our senior people to actively reject these flawed business practices. In essence we need to take ownership of problem. This is clearly an area where the AIP can show leadership.
When I worked for CSIRO we had a discussion about funding new science ideas and the issue arose as to who got the funding. A number of senior people suggested the status quo - that it should be based on the science metrics of the proposer, the citations, the number of grants obtained, and so on. I objected to this as it would prejudice young inexperienced researchers who may still have really good ideas. I proposed instead that the grants be awarded on the scientific merit of the proposal and its potential for applications. If the proposer had little experience then as senior researchers we should mentor them and provide assistance to help make their project a success. Wouldn’t it be wonderful if the Australian Research Council funded projects in this way? While this approach is directed to creating positive scientific outcomes, it is inconsistent with current management practices of working only with the numbers - a practice I call “push-button management”. It is time we changed all this.

And if you are still convinced that the metrics are good, have a read of the criticisms in the Wikipedia article about how the H-index can be manipulated [9]. In particular, see the comment about Google scholar and SCIgen [10] - enjoy!

References

Author biography
Tim Davis holds a Ph. D. in experimental gravitation physics from the University of Melbourne. He worked in CSIRO for 29 years on a broad range of research including atmospheric physics and remote sensing, X-ray phase contrast imaging and instrumentation, high-speed machine vision systems for industry, atom optics and atom waveguides, micro and nanofabrication techniques for sensing systems and document security, biosensor development, nano-optics and plasmonics, as well as observing many dysfunctional “management practices”. In the past he was Secretary and Chairman of the Victorian Branch of the AIP as well as the Convenor of the AIP Science Policy Committee. Dr. Davis is an honorary professor in the School of Physics at the University of Melbourne and is currently a guest professor at the University of Stuttgart in Germany.

Conferences

20-22 April 2017
IRA 2017 – Innovation in Radiation Applications
University of Wollongong, NSW
eis.uow.edu.au/physics/ira-2017

30 April – 1 May 2017
5th International Conference on Biophotonics
Fremantle, WA
www.icob2017.com

5-9 June 2017
Surveying the Cosmos: The Science from Massively Multiplexed Surveys
Sydney, NSW
www.aao.gov.au/conferences/2017SouthernCross

26 July - 1 August 2017
30th International Conference on Photonic, Electronic and Atomic Collisions (ICPEAC XXX)
Convention Centre, Cairns, Qld
icpeac30.edu.au

25-29 May 2019
International Particle Accelerator Conference (IPAC 2019)
Melbourne Convention and Exhibition Centre, VIC
www.ipac2019.org
Walter Harrison’s book “Theoretical Alchemy: Modeling Matter” is the synthesis of a lifetime’s work by one of the world’s greatest solid state physicists in electronic structure theory that should be included in the syllabus of advanced University courses in condensed matter theory at an undergraduate (honours) or graduate level.

At first sight the book, which is only around 200 pages long, appears incredibly simple in formulation, using an analytical (tight binding) methodology to obtain the necessary parameters to describe the plethora of electronic structure properties such as cohesive energy. To describe such an approach as a tour de force would be no understatement.

Years ago in the early 1990’s when I was working at the Fritz Haber Institute in Berlin a well-known German solid state theoretician described Walter Harrison to me as like the Beethoven of condensed matter physics. For me as an experimentalist working in the field of electronic band structure mapping, Harrison was, and still is, a hero and magician par excellence, being able to describe electronic structure of the most complicated systems simply and elegantly in an analytical way. As a PhD student in the 1980’s working on the electronic structure of various systems, such as PdTe2, GaAs and the like, I found that experimental results were useless without direct comparison to electronic structure calculations. A large part of my thesis was about being able to make a useful comparison between experiment and theory and involved state of the art LDA-LMTO (local density approximation - linear muffin-tin orbital approximation) calculations. These days such DFT (density functional theory) has usurped the name electronic structure theory and is even seen by many as simply one of many calculational packages that is run to get an answer concerning fundamental properties.

DFT has met with unbelievable success and won Walter Kohn in 1998 a Nobel Prize in Chemistry for its development. [1]. The success of DFT has gone much further and is used as the necessary gold standard in many serious fundamental condensed matter papers published today because of its accuracy from first principles. One of the major failings of such an approach from my point of view and others [2] is that numbers alone, no matter how accurate, don’t necessarily give a model or understanding of the physics of a particular system. There are potential limits with the theory and so therefore faithfully using computer programs based on particular DFT formulations to produce lots of numbers should be done with great respect.

As Agatha Christie’s, Hercule Poirot put it, “It is the brain, the little gray cells on which one must rely. One must seek the truth within--not without” [3]. Now whether one goes the standard route of DFT or another way, such as the analytical tight binding approach of Harrison, isn’t just a philosophical question, it is one of great prudence. Much of the time an analytical approach will yield the information necessary for a plausible model and understanding without resorting to month long calculations to obtain essentially the same result (albeit with much higher accuracy).

Apart from accuracy, the largest difference between DFT and analytical methods is that a single method DFT approach is used to solve all types systems no matter how complicated or different (whether a H2 molecule or some complex oxide fuel cell material for example), while with the analytical approach of Harrison, all systems are seen as different, requiring potentially different approaches to their study.

The theoretical alchemy found in the title refers to the approach taken by the author in his investigations beginning with the analysis of simpler systems, and then systematically changing them in some way to describe progressively more complex systems. For example, constructing the electronic energy term for Ne and then moving onto other systems by shifting the number of protons amongst nuclei, to, for example, HF, H2O, NH3, CH4, and so forth to construct their energy relationships. The alchemy also employs judicious use of localised atomic and molecular orbitals, free electron like bands, and other descriptions, and in combinations, to describe the important parameters such as electronic coupling. By using experimentally and theoretically
known properties of each system a model and analytical description is developed. To my mind this is the alchemy and the magic or art of such an approach: heavy on ability and thought but much lighter on heavy calculation and much more insightful, useful, and satisfying. The last point is important because an analytical approach enables the scientific method of observation, reflection, and experiment, to be fully employed giving maximum control in one’s own research.

Harrison’s book covers analytical approaches for hydrides, molecules, simple metals, covalent solids, ionic compounds, transition and f-shell metals, transition metal compounds, and has several appendices showing the detailed derivation of various parameters and equations. I thoroughly recommended this book to all condensed matter physicists. It’s a book that we all should know back-to-front and a book that should inspire future work using Harrison’s theoretical alchemy.


[3] from The Mysterious Affair at Styles, A. Christie, see https://en.m.wikipedia.org/wiki/The_Mysterious_Affair_at_Styles?wprov=sfla1

**AAPPS Bulletin**

The AIP is one of 18 member societies of the Association of Asia Pacific Physical Societies (AAPPS). The AAPPS Bulletin, published 6 times per year, is freely available for download. At the time of publication, the most recent issue in vol 27(1), February 2017.

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**From the APPC-AIP Congress, Brisbane, December 2016**

The President of the AIP, Prof Warrick Couch, with the President of the IoP, Prof Roy Sambles.

The President of the AAPPS, Prof Seunghwan Kim, the President of the AIP, Prof Warrick Couch, and the President of the IoP, Prof Roy Sambles, with local indigenous performers at the joint congress dinner.

The winner of the AAPPS Division of Plasma Physics’s S. Chandrasekhar Medal for 2016, Prof Don Melrose, receiving his medal and certificate from the President of the AIP, Prof Warrick Couch, the Chair of the Division of Plasma Physics, Prof Mitsuru Kikuchi, and the President of the AAPPS, Prof Seunghwan Kim.
SAMPLINGS

**Acoustic frequency comb measures up**

An "acoustic frequency comb", which produces sound at a precise set of frequencies, has been made by physicists at the University of Cambridge in the UK. The device, which is an acoustic analogue of an optical frequency comb, works at ultrasonic frequencies. With further improvements, the device could be used for imaging, metrology and materials testing.

**Good vibrations: the frequency comb was found in a silicon wafer**

Conventional optical frequency combs emit a spectrum of light made of thousands of discrete peaks at evenly spaced frequencies, like the teeth of a comb. Developed in the 1990s, such combs have been used in a range of applications such as comparing different atomic clocks.

One way of creating an optical frequency comb is to combine laser light of several different frequencies in a nonlinear optical medium. But in the new work, Adarsh Ganesan, Cuong Do and Ashwin Seshia have discovered that a similar effect occurs when ultrasound waves interact in a silicon wafer covered by a thin layer of aluminium nitride, which vibrates when driven by an electrical signal.

The three researchers were initially investigating if such a wafer could be used for sensing applications when they were surprised to see it vibrate at a number of different frequencies when a megahertz signal is applied to it. The gaps between the frequencies all had the same value (about 2 kHz) and the spectrum looked much like a frequency comb. The teeth of the comb extended over a frequency range of about 100 kHz, says Ganesan.

Puzzled by their discovery, the trio soon realized that their system is like a theoretical proposal for an acoustic frequency comb made in 2014 by Peter Schmelcher of the University of Hamburg and colleagues. Schmelcher’s group modelled the atoms in a solid material as a collection of masses connected by springs that have a restoring force with a nonlinear component.

In such a material, sound waves can interact with each other to create waves at several different frequencies. Ganesan told *Physics World* that while the Schmelcher model does describe some aspects of their acoustic comb, it does not capture the full complexity of the device.

The team is now making more frequency combs and is also thinking about possible applications, which include boosting the accuracy of sensors that operate using mechanical vibrations. Other possible uses include phonon lasers that create phase-coherent sound signals and ultrasonic imaging.


Extracted with permission from an item by Hamish Johnston at physicsworld.com.

**Frogs use non-Newtonian saliva to capture prey**

Frogs capture prey using shear-thinning saliva that spreads over insects when the tongue hits and then thickens and sticks when the tongue retracts – according to researchers in the US. In combination with the tongue’s unique material properties, this two-phase, viscoelastic fluid makes the tongue extremely sticky, allowing frogs to capture and swallow prey heavier than themselves in the blink of an eye. The research could lead to the development of new types of adhesives and material-handling technologies, say the scientists.

A frog retracts its tongue after catching an insect.
Frogs can capture flying insects at astonishing speeds with a flick of their whip-like tongues. But it is not just lightweight insects that they can grab. Research has shown that a frog tongue can pull up to 1.4 times the frog’s body weight. And frogs have been recorded capturing larger animals such as mice and birds.

At the start of the latest study, Alexis Noel, at the Georgia Institute of Technology in Atlanta, and colleagues, filmed common leopard frogs, Rana pipiens and other species capturing crickets with a high-speed camera at 1400 frames per second. They found that a leopard-frog’s tongue can capture an insect in less than 0.07 s – five times faster than humans can blink.

The team’s calculations show that when the tongue is retracting, the force on the insect can reach 12 times that of gravity. The tongue is able to adhere to prey under such forces because it is extremely soft and viscoelastic, and coated in a non-Newtonian, shear thinning saliva, according to the researchers. Shear thinning is the property of some fluids whereby a shear force on the fluid reduces its viscosity. At low shear rates the saliva is very thick and more viscous than honey. But when subjected to high shear forces, for example when the tongue is accelerating in to prey, the saliva thins, becoming around 50 times less viscous, the researchers found.

"During prey impact, the saliva experiences high shear rates, resulting in the saliva becoming thin and liquidy, penetrating insect cracks," explains Noel. "During insect retraction, the saliva experiences low shear rates, firming up and maintaining grip on the insect."

"Frog saliva is much like paint, another shear-thinning fluid," says Noel. "Paint is easy to spread on walls with a brush. Once the brush is removed, the paint then remains firmly adhered to the wall. This is because paint viscosity changes with applied shear rate."

Once the insect is inside the frog’s mouth the shear thinning saliva comes in to play again. The frog retracts its eyeballs into the mouth cavity to push the insect down its throat. This motion produces a shearing force parallel to the tongue that is high enough to turn the saliva thin and watery, and the insect is released and swallowed. The two-phase saliva helps in all phases of prey capture: low viscosity assists during impact and release, while high viscosity assists in prey adhesion.

[Alex C. Noel et al., *Journal of the Royal Society Interface*, **14** (2017); DOI: 10.1098/rsif.2016.0764]

Extracted with permission from an item by Michael Allen at physicsworld.com.

**World’s highest telescope will hunt primordial "B modes"**

Construction has begun on what will be the world’s highest-altitude telescope to study the cosmic microwave background (CMB). The Ngari-1 telescope is to be built at 5250 m above sea level near the Shiquanhe Observatory in Tibet and is expected to be complete by 2021. It will aim to detect primordial "B-mode" polarization of the CMB – the "curl" of polarized CMB light that is considered to be the smoking gun for cosmic inflation – a period about 10^{-38} s after the beginning of the universe.

The telescope is a collaboration between the Institute of High Energy Physics (IHEP) in Beijing and Stanford University in the US, which is one of the leading institutions behind the BICEP telescope in Antarctica. Ngari-1 will observe the northern CMB sky that telescopes from the South Pole or in the Atacama Desert in Chile cannot see and will operate at 90 and 150 GHz. The telescope will contain thousands of microwave detectors, with the exact number depending on funding and the final design. As China does not currently have the capability to fabricate ultrahigh-frequency, high-sensitivity microwave detectors, Stanford is expected to design and build them.

Extracted with permission from an item by Sarah Tesh at physicsworld.com.
Plasma shortens the wavelength of twisted light

A new way of creating twisted light at extreme-ultraviolet (EUV) wavelengths has been developed by Fabien Quéré and colleagues at the University of Paris-Saclay in France. Twisted light carries orbital angular momentum and has a range of potential applications, from boosting the capacity of optical-telecommunications networks to high-resolution microscopy.

The new technique involves first creating a powerful pulse of twisted infrared light by passing a 25 fs 100 TW laser pulse through a 1 mm-thick silica plate with a spiral pattern on it. This twisted light is then fired at a plasma that has been created by heating a silica target with a second infrared pulse. The plasma acts as a mirror that reflects some of the pulse as a twisted light at much shorter EUV wavelengths. Physicists are currently working on several different schemes for making EUV twisted light. Writing in Physical Review Letters, Quéré and colleagues say that such sources "might find intriguing applications as advanced probes of matter". Vortices created within the plasma during the conversion process could also be useful for accelerating charged particles to very high energies – effectively operating as table-top accelerators.


Construction begins on dark-matter detector

The US Department of Energy (DOE) has given the green light for construction of the LUX-ZEPLIN dark-matter detector to start. Located around 1.6 km underground at the Sanford Underground Research Facility in Lead, South Dakota, the experiment will search for weakly interacting massive particles – a leading dark-matter candidate – by using a tank filled with 10 tonnes of ultra-pure liquid xenon. If a dark-matter particle collides with a xenon atom, it will then produce a flash of light that is picked up by around the 500 light-amplifying tubes lining the tank.

LUX-ZEPLIN dark-matter detector given the go-ahead.

LUX-ZEPLIN is expected to be around 50 times more sensitive than its predecessor, the Large Underground Xenon experiment. The start of construction comes after the DOE granted the experiment "critical decision 3", which accepts the final design and allows building work to begin. The DOE’s Lawrence Berkeley National Laboratory is leading the construction of the facility, which includes around 220 participating scientists from 38 institutions around the world. LUX-ZEPLIN is expected to start operation in April 2020.

Extracted with permission from an item by Sarah Tesh at physicsworld.com.

Blocking the symmetry of motion

A mechanical metamaterial that responds strongly to motion from one direction, while blocking it in the other, has been developed by an international team of researchers.

An important property of the new material is its ability to overcome reciprocity – a fundamental principle that
governs many physical systems. It refers to the symmetrical transmission of energy between two points in space. Regardless of which point the energy is travelling from and to, it should behave identically in both directions. Mechanically, reciprocity implies that if you push on one side of an object, you should get the same response if you were to push on the opposite side – the motion travels through the object symmetrically.

Andrea Alù at the University of Texas at Austin in the US has previously worked on overcoming reciprocity for wave propagation. His past work includes producing acoustic isolators that transmit sound in only one direction and antennas that will not listen to their own echo. While Alù was on sabbatical, he and Corentin Coulais of the Foundation for the Fundamental Research on Matter Institute for Atomic and Molecular Physics (AMOLF) in the Netherlands had an idea about a non-reciprocal metamaterial. Coulais previously worked with carefully designed mechanical metamaterials that respond in unusual ways to stimuli, and the researchers decided to combine their interests to produce a mechanical metamaterial that would behave non-reciprocally in response to time-invariant forces.

The researchers designed two non-reciprocal metamaterials that respond much more strongly to forces from one side than from the other. The first was a rubber-made, centimetre-scale metamaterial with a structure like a fish skeleton. It comprised springs arranged with a central spinal column and ribs protruding out at an angle. This structure showed non-reciprocity, but only when sufficiently high forces were applied – springs are fundamentally elastic, so they must be stretched enough to trigger significant rotation of the springs before the onset of nonlinearity.

The researchers’ second design, therefore, consists of freely hinging squares and diamonds, which begin to rotate in response to even small displacements and are therefore non-reciprocal for even small forces. “If you pull it from the right, you displace the material, but only close to where you push or pull on it,” explains Coulais. Such a material could potentially be useful in prosthetics such that an arm can be actuated from one side but not break what it picks up.

[Courentin Coulais et al., *Nature* (2017); doi:10.1038/nature21044]

Extracted with permission from an item by Tim Wogan at physicsworld.com.

**Mobile antineutrino detector could monitor nuclear reactors**

An 80 kg antineutrino detector called MiniCHANDLER will hit the road in April, when it will become the world’s second mobile antineutrino detector, after a similar device was unveiled in Japan in 2014. Built by Jon Link and colleagues at Virginia Tech in the US, the detector uses a solid scintillator that allows it to detect about 100 antineutrinos per day. Antineutrinos are discriminated from much more common background radiation by looking for both the proton and neutron that are produced when an antineutrino interacts with an atom in the detector.

MiniCHANDLER is deployed in a trailer that could be parked next to a nuclear facility, where it would monitor the huge flux of antineutrinos created by nuclear fission within the reactor. Such measurements could, in principle, be used to determine what type of nuclear fuel is being used. This information could be used to ensure that a reactor is not being used clandestinely to create weapons-grade material. If MiniCHANDLER is successful, the team plans to build much larger portable neutrino detectors that could weigh as much as 1 tonne.

Extracted with permission from an item by Hamish Johnston at physicsworld.com.
Coherent Scientific

Andor Launches Ultrafast Spectroscopy-enabled sCMOS Detectors

Andor Technology has released an ultrafast Spectroscopy Mode on its high speed and low noise Zyla and iStar scientific CMOS cameras. Spectroscopists now have access to a unique combination of superb spectral rates, high sensitivity and high dynamic range.

The Zyla spectroscopy mode provides market leading spectral rates up to 27,000 spectra/s, ideally suited for low-light, transient spectroscopy applications with 10’s of microsecond time-resolution. The Zyla’s superb linearity (better than 99.8%) and zero optical etaloning in the near-infrared provide outstanding quantitative measurement accuracy. Its multi-track mode with rates up to 6,000 acquisitions/second delivers a powerful tool for hyperspectral imaging and dual-track, transient absorption spectroscopy at kilohertz rates.

The iStar combines the low noise, high dynamic range and ultrafast spectral rates (up to 4,000 sps) of the sCMOS technology with nanosecond time-resolution. This combination is a highly attractive choice for plasma spectroscopy, laser-induced breakdown spectroscopy (LIBS) or pulsed fluorescence/photoluminescence spectroscopy.

Next Generation COMPex Excimer Lasers

The next generation COMPex lasers come with superior pulse energy (750 mJ at 248 nm) and unrivalled pulse stability (0.75% at 248 nm), ultimate pulse control, and unsurpassed safety in a standard setting footprint.

Featuring new ceramic preionisation, the COMPex provides multi-hundred millijoules output, plus unmatched pulse-to-pulse stability. The COMPex also comes with an improved gas processor that extends both gas and optics lifetimes.

For further information please contact: Jeshua Graham, jeshua.graham@coherent.com.au.

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Lastek

1. TOPTICA presents new TopWave CW UV laser at 266 nm

TOPTICA launches their first member of the new TopWave ultraviolet CW laser series. The ”TopWave 266” provides 150 mW CW output power at a wavelength of 266 nm and <1 MHz linewidth. It stands out with excellent power stability, ultra-low noise operation and a premium beam quality.
The TopWave laser series incorporates successful building blocks from TOPTICA’s scientific tunable UV lasers (e.g. the excellent SUV cavity design) and takes the performance of these lasers to a plug-and-play level. The entire UV beam path is enclosed in an especially sealed compartment. In combination with a fully automated shifter of the SHG crystal this enables a typical lifetime >10,000 hours, which is key for the use in any industrial application.

Due to its reliability and industrial endurance behaviour, the TopWave is an excellent addition to the CW DUV laser market. Future power upgrades and additional TopWave models with other UV wavelengths will be released in the near future.

2. MicroJewel Lasers available from Quantum Composers

The MicroJewel Lasers are a series of rugged, Q-switched, Nd:YAG, DPSS lasers with an ultra-compact design delivering 8 mJ at 1064 nm. Reliable, light-weight and efficient, the MicroJewel lasers are ideal for commercial and OEM applications requiring small form factors.

The MicroJewel is just 3 inches long, weighs only 40 grams and has a compact, inline resonator which will reduce the space and weight limits on laser systems; with low power consumption this laser will be ideal for portable and hand-held applications. It also features an integrated thermal management system designed for applications that require high reliability. In addition, we can customise different optical configurations that are optimised for different parameters (divergence vs energy).

- Wavelength 1064 nm
- Compact, inline resonator
- Efficient, reliable diode pump
- Excellent shot to shot stability
- Pulse Duration (ns) 7.5 ± 1.5 @1064
- Beam divergence (mrad) ≥3.0 @1064
- Beam Diameter (mm) 1.0 ± 0.4

3. Raptor Photonics launches the Falcon III with third generation EMCCD technology

Raptor Photonics, a global leader in the design and manufacture of high performance digital cameras, has launched its latest camera the Falcon III, Falcon II and Kestrel using ground-breaking EMCCD – GEN III technology.

The Falcon III incorporates a new EMCCD sensor developed by e2v which offers 1MP resolution with 10 µm square pixels. A back-illuminated sensor offers a peak QE of >95% offering unsurpassed sensitivity with a total noise floor as low as 0.01 electrons readout noise.

It is three times faster than previous generation EMCCDs with superior linearity and low gain performance. Up to 5000x EM gain can be applied to the sensor using lower voltages resulting in reduced sensor ageing effects. The camera can be cooled to -100°C for lowest possible background events using Raptor’s long life ruggedized PentaVac™ vacuum technology.

For more information please contact Lastek at sales@lastek.com.au

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Warsash Scientific

**Helix Si APD from Excelitas**

Excelitas’ new HeliX Silicon Avalanche Photodiode (APD) Module is a compact, easy-to-use, analogue low-light-level detection (L³D) module employing Excelitas’ leading-edge Si APD chips. The detector is in a hermetic TO package, mounted on a practical OEM based PCB which includes high-voltage power supply, temperature compensation, a low-noise transimpedance amplifier, APD bias monitor and micro-controller.

With this compact voltage-output module, the preamplifier gain is optimized to obtain maximum dynamic range and linearity with the APD at gain adjustable operating voltage. It optimises APD across the 400 nm - 1100 nm wavelength range.

The HeliX APD module is offered with a bare 0.5 mm diameter reach-through Si APD or FC-connector packaging.

Key features include;
- High responsivity: 1300KV/W @ 900 nm.
- Transimpedance amplifier.
- 50 Ω SMA output connector.
- Temperature compensation to stabilise gain and responsivity.
- User controllable gain and responsivity.
- Single +5 V operating voltage at input provides HV and LV internal biases for APD and TIA.
- Front plate can accommodate various APDs.
- ROHS Compliant.

**Sprout-D 532nm pump laser**

Lighthouse Photonics announce the release of the updated Sprout-D™ 532 nm high power pump laser. The Sprout-D is a compact, diode-pumped solid-state (DPSS) laser providing up to 12 W continuous wave (CW) power at 532 nm in a near-perfect TEM00 mode with extremely low optical noise and excellent long-term stability. There are 6 versions available ranging from 5 W to 12 W.

The laser head is a monolithic 3-dimensional design for ruggedness and compactness. The pump diode, integrated inside the laser head, has a typical mean time to failure (MTTF) of more than 50,000 hours to minimize cost-of-ownership. Additional features of Sprout-D include automatic laser power control and both USB and RS-232 interfaces for external monitoring, control and remote service.

Key features include;
- Compact laser head with Seal™ enclosure for long lifetime.
- LockT™ mounting technology locks all cavity optics permanently in perfect alignment.
- Long lifetime pump diode pack integrated inside laser head.
- Extreme low noise <0.03% rms with Noise Elimination Technology (NET™).
- Bench-top, compact power supply with touch-screen control.
- Modular design with disconnectable laser head.

**Nano-FTIR imaging and spectroscopy at 10nm resolution**

neaspec’s revolutionary technology, neaSNOM is the only microscope on the market capable of imaging & spectroscopy in the visible, infrared and even terahertz spectral region at only 10 nm spatial resolution. neaspec’s patented near-field detection technique eliminates the unwanted diffuse light and filters the only 1% small near-field signal out of the scattered light.
Optical imaging is performed by detecting the back-scattered light interferometrically (optical amplitude & phase are acquired simultaneously) while scanning the sample surface topography. By illuminating the AFM-tip with a broadband infrared laser, an IR-spectrum of a 10 nm spot is recorded (nano-FTIR).

Nano-FTIR key features include;
- Reflective AFM-tip illumination
- Detection optimized for high-performance near-field spectroscopy
- Patented background-free detection technology
- Based on optimized Fourier-Transform spectrometer
- Up to 3 spectra per second
- Standard spectral resolution: 6.4/cm
- Upgrade to 3 cm⁻¹ spectral resolution available
- Suited for visible & infrared detection (0.5 – 20 µm)
- Exchangeable beam-splitter mount included
- NEW: Suited for IR synchrotron sources

For more information contact Warsash Scientific at sales@warsash.com.au

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Book reviews & reviewers

Have you read a book recently that might be of interest to other members?

Members are invited to submit reviews of books they have read for publication in the Book Reviews section of Australian Physics.

There is a backlog of books (some on specialised topics, others popularisations) for review. If you are interested in reviewing a book, contact the editor (aip_editor@aip.org.au) indicating your areas of interest.

CALL FOR NOMINATIONS

Walter Boas medal for 2018

This award, named after Walter Boas (University of Melbourne, CSIRO Division of Tribophysics), is for physics research carried out in the five years prior to the date of the award, as demonstrated by both published papers and unpublished papers prepared for publication, a list of which should accompany the nomination.

Any AIP member may make nominations or may self nominate for the award. Nominees should be members of the AIP, Australian citizens and have been residents of Australia for at least five of the seven years preceding the closing date for nominations.

Deadline for nominations for 2018 Boas Medal: 1 July 2017

The Bragg Gold Medal for Excellence in Physics for 2017

The Bragg gold medal for the best PhD thesis by a student from an Australian University was established in 1992 as an initiative of the South Australian Branch, to commemorate Sir Laurence Bragg and his father Sir William Bragg. The purpose of the prize is to recognize the work done by a Ph.D. student in Australia that is considered to be of outstanding quality.

Each Australian university may nominate one candidate. These nominations are submitted to the State Branch committee. The committee selects the best thesis from their State (two for NSW and Vic), and electronic copies (or links) of the selected thesis, citation and referees’ reports are then forwarded to Olivia Samardzic, AIP Special Project Officer.

Nominations from the universities should reach the Secretary of the local State Branch by 1 July 2017

Further details about conditions and procedures for all AIP awards are available on the AIP website: www.aip.org.au.
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