Applied Mathematics

Dr David Williams - Head of Applied Mathematics (from October)

Professor Stephen Hyde - Head of Applied Mathematics (until October)

The Department of Applied Mathematics performs research on fundamental and applied topics in colloid, surface and polymer science, largely in measurement of surface forces; on self-assembly of organic and inorganic structures at mesoscopic scales; and on disordered materials, mostly on micron-scale morphology and transport in porous structures.

http://wwwrsphysse.anu.edu.au/appmaths

Research Summary

After many years of arduous and taxing duty as Head of Department, Stephen Hyde stepped down this year in part to concentrate on his research. Stephen has guided the Department through what could have been a difficult "Post-Ninham" period, in particular through a major review. In fact, in large part due to his efforts, the Department has become significantly stronger and much larger, having approximately doubled in size over the last few years. Our research and funding bases have also broadened considerably.

Early this year we welcomed two new members into the Department, Tomaso Aste and Tiziana di Matteo, who coincidentally celebrated their nuptials at the end of the year. Tomaso has expertise in disordered materials, and in particular in foams and granular media and has a continuing appointment. Tiziana has a background in condensed matter physics, but now concentrates on networks and financial mathematics. Tiziana won a prestigious QEII fellowship in the latest ARC round (one of two awarded to the Department this year). Both researchers were attracted from Italy, and have promised to continue the Department's strong links with the cradle of modern science.

One of the finest strokes of genius of our founder, Barry Ninham, was to create an applied mathematics department that had a strong backbone of experimentalists. In fact, Applied Maths remains first an experimental department but with a number of excellent theoreticians and simulators.

The Department also covers a wide range of research from the very applied and industrial (for instance some of the experimental work done by the paper CRC by Ray Roberts, Tim Senden and Mark Knackstedt), through to the more mathematical and esoteric work on tilings and minimal surfaces done by Stuart Ramsden, Vanessa Robins and Stephen Hyde. In between these two extremes lies the work of much of the Department on surface forces, biophysics colloid science and soft and granular matter. Despite this wide range of activities, our over-riding goal within the Department has always been to carry out curiosity-driven research publishable in high-quality journals.

The Department has a long and proud history of QEII fellowships, starting with Barry Ninham who was the first Australian QEII fellow. This year was probably a first, when the Department won two such fellowships – that of Tiziana di Matteo already mentioned and of Satomi Onishi, who will continue her work on surface forces.

Currently the Department has in fact a large number of ARC fellows, including one Senior Research Fellow, two QEIIs and two Australian Research Fellows.

Although the research interests of the Department are broad they almost all fall under the definition of "materials". There are two general streams of research. One is in "soft matter" and the physical chemistry of surfaces. This deals with all kinds of soft materials such as colloids, polymers and liquid crystals, with a significant emphasis on the interaction forces between particles in fluids. This stream in principle underlies all of biology and many industrial processes. The second, more recent and indeed rapidly growing stream deals with disordered materials, such as rocks and sand. The structures of these materials are very poorly understood and one of the major thrusts of the research is in how we can get a reasonably simple description of these complex materials. This stream has many important applications, not the least to the problems of groundwater modelling and oil recovery. Of course there is substantial overlap between the two streams since many soft materials are substantially disordered. Both streams have industrial applications and funding, but both are studied mainly for their fundamental interest.

Tomaso Aste's research interests cover both groups. He has recently completed some very significant work on the structure of granular materials. As their name suggests these are any materials that consist mainly of grains. Some obvious examples are beach sand, breakfast cereals and gravel. The physics of these systems has been investigated at least since the time of Coulomb in the 18th Century, but over the past decade there has been an explosion of research by physicists on these systems as they exhibit many fascinating phenomena that can be demonstrated cheaply on the laboratory scale and are indeed amenable to computer simulation. Despite a vast amount of work they remain very poorly understood compared to simple liquids and both their statics and dynamics are the subject of some debate. Tomaso has recently shown, using a simple model of hard spheres that the large-scale equilibrium dynamical behaviour of these systems can be understood by examining only a few grains. This work combines statistical mechanics with computer enumeration and has significant overlap with the traditional interest in liquid state theory in the Department personified by Stepjan Marcelja who has temporarily left the Department to become Head of the Boscovich Institute in Croatia. Tomaso also has interests in disordered systems generally, particularly networks.

As mentioned previously the Department this year welcomed Tiziana di Matteo, who has recently begun studying "econophysics". This subject seeks to apply the methods of theoretical physics and in particular statistical physics to the empirical analysis of financial markets data (complex data sets). For interest rates data, the study has been mainly focused on the "tail" regions of the fluctuations probability distributions and on the correlations among time series at different maturity dates. The correlations have been analysed through the geometrical and topological properties of their metric graphs. Tiziana also studies complex systems in general by using techniques of statistical physics, non-linear dynamical analyses and numerical computational methods.

Stephen Hyde has a strong overlap of research interests with Tomaso and Tiziana. Despite being Department Head for much of 2002, he made progress in three areas. These are: (1) Euclidean crystalline networks from 2D hyperbolic tilings; (2) Growth of complex self-assembled inorganic materials and (3) Computational geometry and self-assembly. Stephen Hyde, amongst the senior people, is probably the most mathematical, with a special emphasis on geometry, usually on the non-Euclidean kind. However, this does not stop him having a keen interest in, and indeed in performing experiments, particularly those that lead to novel materials.

Stephen's work on tilings involves extensive numerical applications as well as recent tiling theory, group theory, surface geometry and topology and non-Euclidean geometry. A complete algorithmic suite is now done and the automatic generation of networks in 3D Euclidean space by projection onto regular triply-periodic minimal surfaces is about to start. The long-term goal is to produce catalogues of networks to study the relative importance of network topology and geometry in their allowed geometrical fluctuations, transport efficiency and general statistical physics. This work is done in collaboration with Stuart Ramsden, Tiziana Di Matteo and Vanessa Robins.

Anna Carnerup, Arthur Sakellariou, Ray Roberts, Tim Sawkins and Tim Senden with the newly built an commissioned X-Ray Computed Tomography Machine. This an in- house piece of equipment allows full 3D images to be made at a resolution of 5 microns

Bubbles levitating by expulsion of carbon dioxide gas . An experiment by Tim Senden and Jean-Marc di Meglio

Stephen Hyde's work on growth of complex self-assembled inorganic materials is in part done in collaboration with Dr Garcia Ruiz in Granada, Spain. It centers on investigations of the structures of carbonate-silica complexes grown in the lab under ambient conditions. The growths are interesting for a number of reasons: they are mimics of purported microfossils; include the oldest known terrestrial "fossils"; they exhibit complex orientational ordering without long-range translational order; and they are interesting model systems to compare with biomineralisation processes in living creatures. Some of this work is done in collaboration with Andy Christy, Anna Carnerup and Ankie Larsson.

Stephen Hyde has long had an interest in computational geometry and self-assembly. Current work in this area includes the work with Gerd Schröder on medial surfaces and medial axes, that will allow rigorous calculations of the relative stability of various morphologies (eg. bicontinuous and mesh mesophases in lyotropic liquid crystals). Apart from her work with Stephen Hyde, Vanessa Robins has worked on a project with Liz Bradley at the University of Colorado, Boulder. They have developed new applications of computational topology in the analysis of data. Specifically, removing noise from chaotic time-series data, and extracting coherent features from scientific images such as cell micrographs and satellite images. Vanessa Robins continues to collaborate with Klaus Mecke in Germany on analysing topological signatures of point-patterns.

Mark Knackstedt leads a large group devoted to the understanding of the structure of disordered materials and also to the properties of fluid flow within such materials, particularly rocks and other porous matter. He also leads one node of the Cooperative Research Center for Functional Communication Surfaces which deals mainly with fundamental problems affecting the paper industry. This node either in whole or part funds several people within the Department. Within this group Ray Roberts has been examining how liquid deposited on a paper surface is imbibed into the bulk of the paper. Using scanning electron microscopy and Raman microscopy, he had previously shown that the rate of liquid imbibition affects the quality of low pressure melamine panels. He also showed that the usual measures used in industry are deeply flawed. More recently, using cryo SEM and two-photon laser confocal microscopy, he has been able to determine the mechanism of liquid imbibition in paper as being film flow in interfiber channels as opposed to piston flow in pores which has been the popular belief/theory for the past 100 years. He is now looking at the structure of paper using the MicroCT and trying to identify how it affects the rate of liquid imbibition and in particular the actual network pathway of an imbibing liquid.

Within the porous materials group Adrian Sheppard has continued his work on the flow of fluids in porous materials, which has applications to the oil industry. The flow of multiple immiscible fluid phases through a porous medium involves numerous factors. Capillary and viscous forces both play a role, while flow occurs in wetting films along the walls of the medium as well as through the bulk of the pore space. An understanding of how the thickness of these films evolves is a critical foundation of any accurate model of this process. We have developed a model that, for the first time, correctly models the dynamics of film flow and film thickening within two- and three-phase flow. Implementation of this new model into our existing network modelling software is well under way.

Also within the group interested in porous and disordered media are two Germans, Lydia Knuefing and Christoph Arns. Lydia has begun to analyse images of porous media. Convinced that a 2D analysis can not capture the nature of connectivity in a 3D structure, Lydia has started to investigate the use of a 3D-Fourier analysis on images we have taken with the Department's MicroCT facility. By using only part of the frequency spectrum when transforming from Fourier-space to real-space, the original image undergoes a process that seems to be similar to a dilation process, i.e. depending on the cut-off small-scaled features of the original image vanish, thus revealing areas of close- or loose-packed material. Whether these are truly responsible for most of the fluid flow has still to be investigated.

Christoph Arns has started a new collaboration with Professor D. Stoyan, University of Freiberg, Germany, carrying out a geostatistical analysis of tomographic data. He also continued his work with Mark Knackstedt and extended the physical properties they calculate for tomographic data sets of rocks to NMR relaxation. Here in particular they looked at the inversion of NMR relaxation curves, which is an ill-conditioned problem and involves the inversion of a Laplace-transform. For this one needs regularisation techniques and Christoph implemented several different ones.

The Department has long had an interest in, and in fact been one of the world leaders in the field of colloid science, and physical chemistry in general. This field deals with interactions between solute particles, from molecules to proteins and polymers in solution, to suspensions of colloidal particles, and these in turn determine the properties of most real world systems. Examples include self assembly of biomembranes, reactivity in biotechnologies and biochemistry, chemical synthesis, and a host of chemical engineering applications, from minerals processing, oil recovery to soil science and detergent formulation and drug delivery. The entire theoretical framework of physical chemistry that underpins such applications is so well established that it is hardly ever questioned. A naive observer might therefore expect to call on an array of theories that offer some quantitative guide to developments in industry and the biosciences. The truth alas lies in the opposite direction. We take as an example what ought to be the most applicable field, colloid science. A perusal of the standard textbooks and monographs in this area reveals a degree of triumphalism, but contains not a hint of its current embarrassing state. While there are many accurate and detailed experimental measurements almost no results are known where theory and experiment agree. In some cases there is a limited understanding, but no predictability. Almost the whole field is empirical. It abounds with fitting parameters and phenomenological rules. One strong thrust of research in the Department is to address these problems. This is being done from a theoretical viewpoint by Mathias Boström, David Williams and Barry Ninham. There are also experiments in this area being conducted by Vince Craig and Vassili Yaminsky.

The major problem with current theories is that they almost all assume that electrostatics dominates all the interactions. In fact for many systems, and indeed for almost all biological systems, the salt concentration is high and the electrostatic

Spirula shell imaged by the department's X-ray Computed Tomography Machine interaction is strongly screened. This means that other forces become dominant and the classic example which we have focussed on is dispersion forces.

The team of Boström, Williams and Ninham has recently applied these ideas to a number of systems of interest to the physical and biophysical community. In particular we have revamped the old "DLVO" theory of the interaction between charged colloids to show that it is invalid at reasonable salt concentrations. We have also examined the behaviour of ions near membranes and DNA. In general, our major result is that almost the whole of colloid science and molecular biophysics needs to be re-examined since the fundamental assumption that electrostatics dominates is wrong. In particular, almost all molecular simulations of biological systems must be called into question.

The Department has had a long history of using the Surface Forces Apparatus to measure molecular forces. One project which was recently undertaken by Vassili Yaminsky and Andrew Stewart was the first direct high-resolution measurements of dispersion force against distance between crossed cylindrical mica surfaces in air with a surface force apparatus that detects displacement by means of a capacitor with a resolution of 0.1 nm. The surface forces apparatus has also been used by Satomi Onishi and Andrew Stewart to measure frictional forces at low humidity. In this regime the surfaces slide without shearing. The dynamic shear stress decreased with increasing humidity and a mechanism based on capillary condensation is proposed to explain the role of humidity on friction by adsorption of water layers on the free mica surfaces, and at the contact.

Vince Craig has continued and extended his work on nanorheology and in particular the effect of slip between a fluid and a solid interface. In classical fluid dynamics it is usually assumed that there is no slip between a liquid flowing in a pipe and the walls of the pipe, i.e. the liquid is at rest at the walls. This however is only an approximation and there has been a growing body of evidence that slip occurs at walls. In large pipes, such as those used for the transport of domestic water this slip is of no consequence. However for very small systems with length scales of order 1000 Å this slip has dramatic effects. In particular Vince Craig and Chiara Netto have shown experimentally using an atomic force microscope that slip can substantially change the force between a small sphere moving towards a fixed plane. This, apart from being of fundamental importance, will be crucial in understanding the lubrication of nano-machines. Vince also spent a few months towards the end of the year at the YKI in Sweden where he collaborated in several projects of importance to the paper industry.

Ira Cooke and David Williams have investigated the collapse of semiflexible polymers. In the past year our work on the collapse of copolymers has been extended to include chains with varying degrees of stiffness. Many important polymers are stiff over length scales of several subunits. These include biological polymers such as DNA and Actin and synthetic polymers such as those that conduct electricity. By modelling the collapse of polymers with various stiffness properties we have observed a wide variety of collapsed structures at the nanometer length scale including rods, toroids, striped toroids and networks.

This year also saw a large amount of equipment installed within the Department, much of it carried out by Tim Senden with the help of technicians Anthony Hyde and Tim Sawkins, both of whom were awarded well-deserved medals for General Staff Excellence in 2002.

The minimal surface formed by a soap film on a wire frame, draped over the corresponding solid surface

The equipment highlight was the building of our X-Ray CT machine which allows full 3D images of materials with resolution down to the micron scale. This will greatly enhance the research capabilities of the porous media group. An Imaging Ellipsometer was installed which allows detailed examination of thin surface layers. A new Atomic Force Microscope was installed with total-internal-reflectance fluorescence microscopy capabilities. This will allow detailed examination of surfaces and a number of experiments involving the manipulation of individual molecules. Tim Senden also continued his applied biological work with Vimed Biosciences and signed a five-year research agreement to develop to the clinical stage a medical diagnostic agent for the detection of blood clots.

As a final point, in November this year the Department held the second annual Kiola conference, which allowed everyone in the Department to present a slice of their work. This meeting also involves a few honoured outside guests and presents the work of the Department in a primitive but relaxed environment.

STAFF

Professor and Head of Department

Stephen Hyde, BSc PhD Monash (until October)

Senior Fellow and Head of Department

David Williams, BSc Sydney, PhD Cambridge (ARC Fellowship, University of Sydney) (from October)

Professors

Stephen Hyde, BSc PhD Monash (from October)

Barry Ninham, MSc WA, PhD Maryland, DTech (hon causa) KTH Stockholm, D Phil (hon causa) Lund, FAA (Visiting Professor, University Florence, Italy, April – December)

Senior Fellows

Andrew Stewart, MA ScD Cambridge, AM Harvard, EE Col, DIC PhD London, FAIP

Vasili Yaminsky, DipHons PhD Moscow

Fellow

Tomaso Aste, DipHons Genova, PhD Milan

Mark Knackstedt, BSc Columbia, PhD Rice (jointly with School Pet. Eng., UNSW) (ARC QEII Fellowship)

Research Fellows

Andy Christy, MA PhD Cambridge

Vince Craig, BSc PhD (ARC Fellowship)

Satomi Ohnishi, BSc SUT, PhD Saitama

Tim Senden, BSc PhD (ARC Fellowship)

Adrian Sheppard, BSc Adel, PhD

Adjunct Fellows

Rob Sok, BSc PhD Gronigen

Post-Doctoral Fellows

Christoph Arns, Dipl-Phys Aachen, PhD UNSW

Armin Bauer, Dipl-Chem Dr.Rer.Nat Regensburg

Tiziana Di Matteo, BSc PhD Universita' di Salerno

Ann-Kristin Larsson, MSc Lic PhD Lund, Doc Stockholm

Vanessa Robins, BSc MSc, PhD Colorado

Arthur Sakellariou, BSc PhD Melbourne

Computational & Visualisation Consultants

Stuart Ramsden, GradDip Film & Television Swinburne

Ray Roberts, BSc (CRC Administrator)

Adam Stone

Visiting Fellows

Mattias Boström, MSc PhD Linkoping

Anna Carnerup, BSc Malmo (from February)

Georges Debrégeas, PhD Paris VI

Jean-Marc di Meglio, PhD Paris VI

Eugene Gamaly, PhD DSc Moscow

Bruce Hyde, BSc Bristol, PhD DSc

Siewert-Jan Marrink, PhD Groningen

Yoshinori Nagai, DSc Waseda

James Quirk, DSc WA, AO, FTS, FAA

Nicholas Welham, BEng Leeds, PhD Imperial College

Senior Technical Officers

Anthony Hyde, Assoc IE Aust

Tim Sawkins

Departmental Administrators

Vicki Beissner (part-time) (until May)

Cindy Bradley (part-time)

Atomic & Molecular Physics Laboratories

Professor Brenton Lewis
Head of Atomic & Molecular Physics Laboratories

Atomic, molecular and optical physics is both a fundamental and enabling science that supports many other important areas of science and technology. Staff of these Laboratories pursue a broad spectrum of experimental and theoretical research into the structure of atoms, molecules, and solids, and their interactions with electrons, positrons, and photons.

http://wwwrsphysse.anu.edu.au/ampl

Research Summary

As recognised by the Division of Atomic, Molecular, and Optical (AMO) Physics of the American Physical Society, "AMO physics is an enabling science that supports many other important areas of science and technology." Indeed, students graduating in AMO physics acquire a breadth of knowledge and skills, enabling them to contribute to many areas of science, technology, and society. AMO physicists have also appeared prominently among Nobel laureates in recent times. The Atomic and Molecular Physics Laboratories are engaged in a broad range of experimental and theoretical studies of the interaction of electrons, positrons, and photons with atoms, molecules, and solids, in order both to further our knowledge of fundamental physical and chemical processes, and to provide essential information that is critical to applications in other scientific disciplines, technology, and the environment.

There has been greater stability in the Departmental structure this year. Professor Erich Weigold retired in October as School Director and now occupies the special position of PostDirectorial Fellow in the Department. We thank him for his guidance as Director and look forward, as he is, to a period of relaxing, but productive, research. During the year, Professors Robert Robson and Erich Weigold both completed their duties as Humbolt Fellows in Germany. The Department also welcomed Professor Harald Friedrich as a Visiting Fellow (jointly with the Department of Theoretical Physics [TP]), together with two new research students, Ivan Blajer and Milica Jelisavcic. In addition, we hosted six Winter and Summer Scholars who were involved in brief research projects. Congratulations are also in order for Brenton Lewis, who was promoted to Professor, and Maarten Vos and Julian Lower, who were promoted to Senior Fellow and Fellow, respectively. Finally, construction started this year on the new building wing which will house most of the Department's experimental laboratories after 2003. Together with the concurrent refurbishment of the East Cockcroft wing, this important development will serve to consolidate Departmental staff and activities, currently in disparate locations, into a single area. We look forward to the improved intra-Departmental interactions likely to result from this development.

Members of the Department were again successful in winning grants, awards, and other marks of distinction during the year. The grant success has been particularly significant to the future of the Department, considering that this has been the first year of the Institute's full eligibility for Australian Research Council grants. The Department won four grants in the ARC Discovery round, resulting in funding on the order of $500,000 p.a. The successful proposers included Professors Steve Buckman and Erich Weigold, and Drs Andrew Truscott, Julian Lower, Maarten Vos, and Anatoli Kheifets. Professor Buckman was outstandingly successful, winning two Discovery and two Linkage grants at a success rate of 100%! Toward the year's end, the ANU was successful in obtaining ARC funding for a Centre of Excellence in Quantum Atom Optics. The Department shared in this success, through the efforts of Dr Andrew Truscott and Dr Ken Baldwin (Laser Physics Centre [LPC]), obtaining funding on the order of $300,000 p.a. which will enable the pursuit of a major new project in the area of Bose-Einstein condensates, together with other collateral support. Professors Brenton Lewis and Bob McEachran, together with Drs Steve Gibson, Anatoli Kheifets, Jim Mitroy (Northern Territory University), and members of other departments, were also successful in obtaining Major Equipment Committee funding for a fast workstation to enable the simultaneous interactive pursuit of computer-intensive theoretical research projects. The second tranche of Institute Planning Committee funding was received by the School during the year, partly for the appointment of an atmospheric modeller to the Solar-Terrestrial Environmental Programme (STEP) of the Department. Dr Frank Mills, of the Jet Propulsion Laboratory, Los Angeles, has been appointed to this position, held jointly with the Centre for Resource and Environmental Studies, and is due to start in 2003.

Finally, during the year, Professor Bob Crompton was greatly honoured to have been made an Honorary Fellow of the Australian Institute of Physics, Professor Brenton Lewis was elected to Fellowship of the Optical Society of America, Colin Dedman was awarded

Professor Lewis Chadderton honoured by the International Nuclear Track Society - Jubilee Congress, New Delhi, November 2002

a Council Medal for general-staff excellence, Professor Lewis Chadderton was awarded Honorary Membership of the International Nuclear Track Society, and Dr Steve Gibson was elected to Council of the Australian Optical Society. Dr Anatoli Kheifets was again honoured by the holding of the second Anatoli Kheifets Workshop on Atomic Photoionisation in Japan.

The international profile of the Department remains strong, as evidenced not only by continuing receipt of international awards and learned-society fellowships, but also by 13 invitations to speak at mainly international conferences, and an ongoing commitment to 35 collaborative projects, most involving international collaborators. Of approximately 50 refereed Departmental publications this year, nearly two-thirds have international coauthors.

A brief summary of the research activities in the Department is given below. Those readers requiring further details should view the projects listed in Section 3 under Collaborative Ventures, and/or download manuscripts for the publications listed in Section 5. Details of some of the collaborative projects of AMPL staff members may also be found in the LPC and TP reports. In the broadest sense, the Departmental research activities in AMO physics, both experimental and theoretical, may be classified principally under three headings (although there is some cross-fertilisation): atom manipulation, electron impact (including positrons), and photon impact.

Atom Manipulation

The Atom Manipulation Project is a joint program between AMPL and the LPC which uses laser cooling and trapping techniques for atom-optics and atomic collision experiments. Activities this year have centred on improvements to the metastable He atom trap and theoretical modelling of soliton trains formed in a quasi one-dimensional Li Bose-Einstein Condensate (BEC). A new activity, the creation of a metastable He BEC, will be established by Dr Truscott, following the award of ARC Centre of Excellence funding for the Centre for Quantum Atom Optics.

Electron Impact

Low-Energy Electron Scattering from Atoms and Molecules

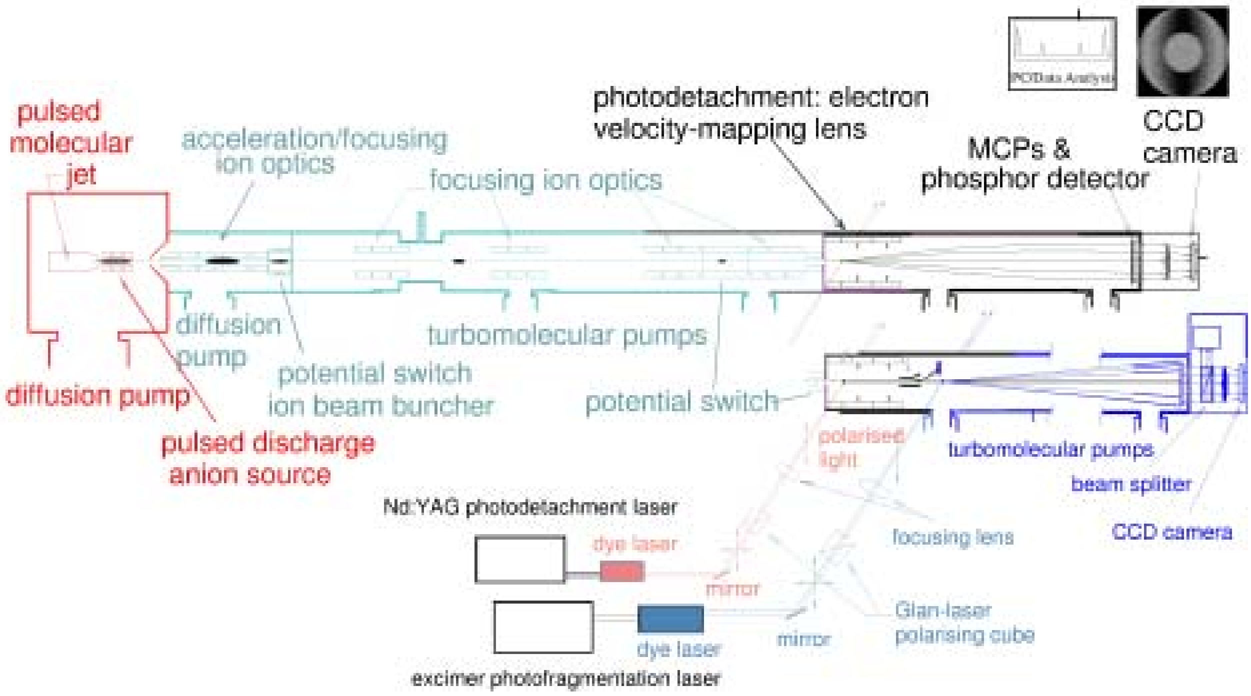
Following a major overhaul of the crossed-beam apparatus in the early part of the year, measurements of differential cross sections and excitation functions for ethylene have been completed and a series of measurements on very-low-energy electron scattering from nitric oxide have commenced. Both molecules are of fundamental and environmental interest, especially at low impact energies. A major review article on electron-molecule scattering cross sections by Brunger and Buckman was published in 2002 in Physics Reports.

Electron Scattering from Metastable Helium

Progress has been slow on the measurements of absolute total scattering cross sections from trapped metastable He (2^3S). The main problem has been maintaining sufficient atom density in the trap after the trapping fields are turned off. Several schemes, including optical molasses and atom release and recapture are being investigated in order to overcome this problem.

Quantum-State-Resolved Electron-Impact Ionisation

In this experimental program, kinematically-complete (e,2e) coincidence techniques, in conjunction with spin-resolved beams of electrons and target atoms, are used to obtain detailed



Schematic Diagram of the photofragment spectrometer

knowledge of the process of electron-impact ionisation, thus sensitively probing the many-body behaviour of groups of interacting electrons, the understanding of which is central to the description of a wide range of physical phenomena. Significant developments in instrumentation have occurred this year. Our double-toroidal spectrometer, which simultaneously detects two electrons over large ranges of scattering angles and energy, can now accurately measure weak processes, such as simultaneous ionisation and excitation, at the 0.1% level. In addition, the feasibility of triple-coincidence measurements has been demonstrated.

Electron-Momentum Spectroscopy (EMS) of Solids

EMS measurements of ultra-thin single-crystal silicon have revealed details of the anisotropic electronic structure, as well as a wealth of diffraction effects, and are likely to provide a great test case for many-body perturbation theories. Construction of a new electron-beam evaporator has made the study of a large variety of metals possible, leading to new insights into the energy-resolved momentum densities of iron, nickel, and copper. Construction of a polarised electron source, which will enable the study of magnetic films by EMS, is well underway. Finally, our theory of electron correlation in solids has been tested in a series of local experiments. In particular, theoretical results on light *s, p* elemental solids have been confirmed experimentally.

Elastic Scattering from Hydrogen in Solids

Both electron and neutron scattering studies provide information on the momentum distribution of hydrogen in materials, but there are inconsistencies between results provided by the two techniques. Beam time has been awarded at ISIS, the world's leading facility for the production of neutrons, for a comparative study of neutron and electron scattering from nuclei, with a view to solving this puzzle.

Multiple Atomic Ionisation

The theory of multiple atomic ionisation has been further developed to include low-energy electron impact, complex atomic targets, and simple diatomic molecules. Experiments at the Max Planck Institute for Nuclear Physics, Heidelberg, and the Photon Factory, Tsukuba, have confirmed key predictions of the theory.

Electron-Impact Excitation and Ionisation of Atoms

The calculation of accurate triple differential cross sections for inner-shell ionisation of atoms remains a challenge. The role which exchange plays in these ionisation processes has been investigated and significantly improved agreement with experiment obtained. Fully relativistic calculations of atomic excitation cross sections and spin-dependent parameters have proved successful, but it is desirable to extend this method through second order.

Positron-Impact Excitation and Ionisation of Atoms

Following improvements in the energy resolution and intensity of positron beams, the first cross section measurements of the first two fine-structure levels of Ar have become available. Relativistic distorted-wave calculations of these cross sections have been carried out and satisfactory agreement with experiment obtained. However, it is clear that positronium formation needs to be incorporated into these calculations, as well as those for ionisation.

Momentum-Transfer Cross Section for Mercury

Accurate low-energy cross sections for electrons in mercury vapour are needed for modelling mercury discharges in lighting devices. The first theoretical calculation to substantially agree with the experimental low-energy momentum transfer cross section have been performed. Because of the toxic nature of mercury, zinc is currently being investigated as a replacement in lighting devices. Thus, similar calculations of the total and momentum transfer cross section are being extended to zinc.

Electron-Hydrogen Vibrational Excitation

The suitability of the semi-classical Boltzmann collision operator for describing electron-molecule collisions involving rotational and rovibrational excitation continues to be investigated, in order to resolve the well-known and long-standing swarm experiment-quantum theory-beam experiment stalemate for electron-hydrogen scattering.

Negative Mobilities and the Second Law

Recent theoretical predictions of negative mobilities seem to imply Joule "cooling" and violation of the Second Law of Thermodynamics, but closer investigation through non-equilibrium thermodynamics reveals that total entropy production is indeed positive, and the Second Law remains intact. However, the same analysis shows that traditional swarm experiments will never be able to observe such negative mobility phenomena, as these experiments measure the "bulk" drift velocity, which is always positive.

Non-Hydrodynamic Transport Phenomena

The modern study of transport phenomena in ionised gases is chiefly motivated by the need to understand the behaviour of low-temperature plasmas in the neighbourhood of sources and boundaries where gradients may be large and distinctly non-hydrodynamic conditions prevail. These problems are of fundamental physical interest and are being investigated through

Photon Impact

Vacuum Ultraviolet (VUV) Laser Spectroscopy (jointly with the LPC, incorporating the STEP)

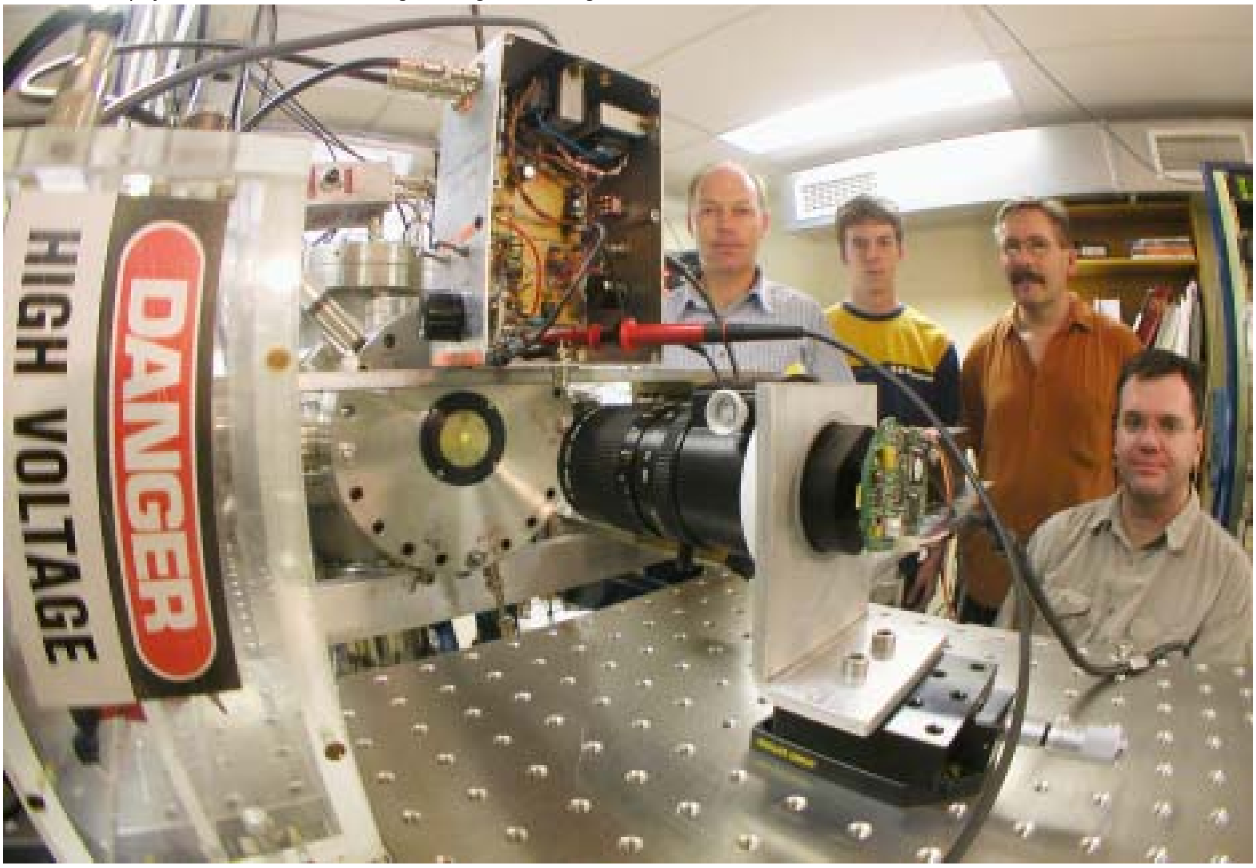
The work under this program is aimed at developing and applying high-resolution widely-tunable, coherent sources of VUV radiation to studies of the structure and photodissociation dynamics of molecules of atmospheric and environmental interest. Activities this year have centred on the development and characterisation of a new, high-resolution, pulsed laser source based on a periodically-poled KTP crystal in a ring-cavity optical parametric oscillator (a joint ARC project with Macquarie University), together with the first laboratory measurements to demonstrate quantum-interference effects in the Schumann-Runge band spectrum of molecular oxygen.

Photodetachment and Photofragment Spectroscopy

Good progress has been made on the construction of the fast-beam photodetachment and photofragment spectrometer, despite several long delays associated with equipment failure. A new electron imaging system for photodetachment spectroscopy (Velocity Map Imaging) has been implemented, enabling the simultaneous acquisition of high-resolution photoelectron spectra and full angular distributions. The first data, on molecular oxygen, are expected in 2003.

Close-Coupled (CC) Spectroscopy

In this computational program, the techniques of scattering theory are applied to the "half-collision" process of molecular photodissociation, CC procedures allowing the treatment of complex interactions between the molecular excited states. This

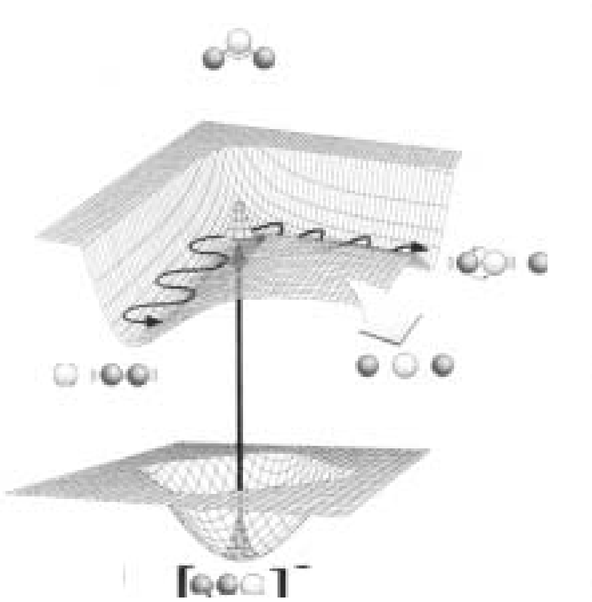


The photofragment spectrometer with some usual suspects year, there has been further development of a model of molecular oxygen photodissociation, with applications in the field of terrestrial-atmospheric photochemistry, together with the first steps towards the construction of a CC model of molecular nitrogen photodissociation in the extreme ultraviolet, with applications in the interpretation of NASA-mission data from past and future planetary encounters with, e.g., Titan, Triton, and Pluto. An essential aspect of the CC model development involves the analysis and interpretation of experimental data from a number of international laboratories, e.g., SRI International (San Francisco), Edinburgh University, and Vrije Universiteit (Amsterdam), giving a strong international collaborative flavour to the CC program.

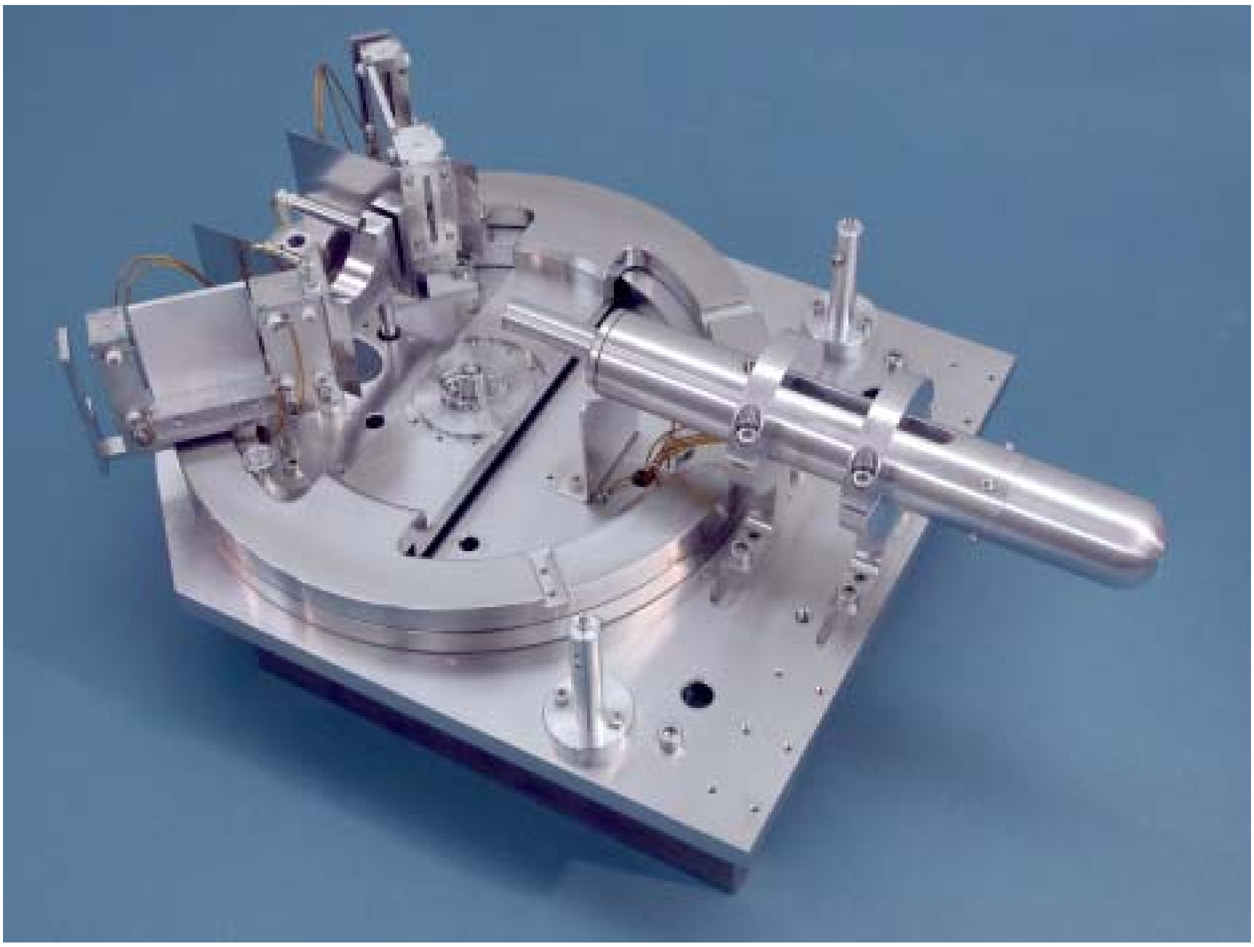
Other Areas

Nanostructure of Opal

Opal consists of spheroids of silica gel, about a quarter of a micron in diameter, arrayed periodically. This period, which is comparable to the wavelength of visible light, gives rise to the optical bandgap effects that give opal its characteristic lustre. Investigations have been made by Atomic Force Microscopy of the cleavage structure of opal. The nuclei of the spheroids, a few nm in size, are found to behave mechanically in a way different from the bulk. The composition of opal, particularly of the nuclei, is being investigated by chemical and nuclear analysis.



Transition state spectroscopy is studied using the coincidence photofragment/photodetachment spectrometer. The stable negative ion accesses the unstable (transient) neutral species, opening a window into the intermediate zone between reagents and products of chemical reactions



Collimating optics, deflectors and Faraday cup from the Electron - Momentum - Spectroscopy of Solids apparatus

Staff and students of the Atomic and Molecular Physics Laboratories 2002

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Technical Officer

Gary Picker, AssocDipMechEng CIT

Departmental Administrator

Alice Duncanson

Research Accomplishments

Electronic Materials Engineering

Professor Rob Elliman - Head of Electronic Materials Engineering

The Department of Electronic Materials Engineering conducts interdisciplinary research on the physics and engineering of electronic and optoelectronic materials and devices.

http://wwwrsphysse.anu.edu.au/eme

Research Summary

Modern integrated electronic and optoelectronic devices are practical examples of the spectacular advances in condensed matter physics, materials science and device engineering. The Electronic Materials Engineering (EME) Department contributes to these advances by undertaking world-class research in areas involving the growth, structure, properties and applications of electronic materials. Individual projects range from fundamental, curiosity driven studies of novel solid-state phenomenon to strategic or application-driven device engineering. Indeed, the diversity of the Department's research is one of its key strengths, underpinning its broad collaborative base and its ability to attract students and researchers from a range of disciplines.

This was an exciting and eventful year for EME with many significant personal and scientific achievements and many new developments and changes. The year also involved a degree of uncertainty, introspection, anticipation and exhilaration, as staff changes and full entry into the ARC competitive grants scheme had their impact. On the research front, productivity remained impressive, with over 58 papers published in peer-reviewed journals and around 15 invited or keynote talks presented at national or international conferences. The Department's extraordinary success in the 2003 competitive grant scheme (a success rate of over 85% compared to a national average of around 25%) was another major highlight of the year which clearly reflected the quality and strength of its research program. This success will see several new early-career researchers joining the Department in 2003, adding further to its vitality and energy. It will also see the total income from ARC competitive grants exceed that of recurrent funds from ANU, a situation that presents exciting new opportunities as well as interesting challenges.

As in previous years, the outstanding contributions of EME staff and students have been recognised by a range of promotions, appointments and awards. These are detailed later in this report but several are worth noting here. In particular, the promotion of C. Jagadish to academic level E2 and his election to Fellowship of the Australian Academy of Technological Sciences and Engineering (ATSE), together with the promotion of H.H. Tan to academic level C and P.N.K. Deenapanray to academic level B were well deserved. On the student front, Jodie Bradby was awarded a highly-regarded Australian-American Fellowship for study in the USA and was additionally awarded the Materials Research Society (MRS) Gold Medal for the best oral presentation at the 2002 MRS Fall Meeting. COMMAD 2002 poster awards were garnered by Christine Carmody and Penny Lever. In addition, three EME students were awarded PhDs (Michael Cohen, Stephanie Cheylan and Sergei Kucheyev), and three others submitted their theses for examination (Jodie Bradby, Chris Glover and Tessica Weijers). Sergei subsequently accepted a prestigious Lawrence Fellowship to work at Lawrence Livermore National Laboratory in the USA.

The year also saw several staff changes, including the departure of Laura Walmsley, our Departmental Administrator, and of two experienced technical staff, Alan Hayes and Tony Watt. Having worked in EME for around 5 years, Laura has now been appointed as Personal Assistant to the Director of the School. During her time in EME her contribution to the smooth and efficient operation (and social well being) of the Department was much appreciated. Renee Vercoe will take over Laura's role early in 2003. Other staff changes were precipitated by a review of EME's technical staff, together with a University-wide voluntary redundancy scheme. This resulted in Tony Watt and Alan Hayes taking redundancy packages. Tony and Alan were responsible for the maintenance and development of EME's high-profile accelerator laboratories and had accumulated around 20 years of total experience in this area. The loss of their skill and expertise will certainly impact on the operation of the accelerator laboratories throughout 2003 and beyond.

The strength of EME's research program continues to be underpinned by the performance and reliability of its extensive suite of experimental equipment and associated facilities and infrastructure. These continue to grow each year, with a new photoluminescence laboratory and extensive clean-room suite being installed during 2002. The latter owes much to Michael Aggett who was largely responsible for the technical design and management of the project. The fact that the Department's equipment and facilities continue to operate at peak performance and with minimal down-time is a great credit to the Department's technical staff (M. Aggett, T. Halstead, A. Hayes, B. King, and A. Watt), technical assistants (M. Conway and A. Williams) and associated research assistant (D.J. Llewellyn). Their expertise, commitment and professionalism are much appreciated. The crucial role played by the School's workshops and service areas is also gratefully acknowledged in this context.

Material Growth, Synthesis and Processing

MOCVD Growth of III-V Semiconductor Structures

The growth of epitaxial III-V semiconductor structures by metal-organic chemical vapour deposition (MOCVD) is an active area of research with several new material systems and structures being investigated this year. Highlights included the growth of highly strained InGaAs and InGaAsN structures for long wavelength (1.3 and 1.55 µm) optical communications, which resulted in InGaAsN quantum wells having room-temperature optical emission at 1.21 and 1.320 µm, respectively, and a novel scheme of inserting InAs monolayers in GaAsN quantum wells to increase luminescence efficiency, a process that looks promising for device applications. Work also continued on the growth of high-In content quantum dots and stacked dot layers. In order to reduce the strain in stacked quantum dot structures a strain-compensating scheme was proposed and implemented, in which, InGaAs dots were grown on a thin buffer layer of pseudomorphic GaP. It was found that there was substantial improvement in the uniformity, size and thermal stability of the dots although a blueshift in the emission wavelength due to intermixing of the InGaAs and the GaP layer was observed. These layers are now being investigated for their suitability in device structures which require higher temperature growth.

Intermixing for Optoelectronic Device Integration

Impurity-free disordering (IFD) of III-V semiconductors is a promising candidate for the monolithic integration of optoelectronic and photonic devices. The underlying operative mechanisms of this apparently simple process are, however, not well understood. Our recent studies of bulk GaAs, InP/InGaAs heterostructures and InGaAs/GaAs quantum dot structures have provided insight into these mechanisms, showing, for example, that stress-induced conversion of gallium vacancies into arsenic anti-sites can reduce the efficiency of IFD in bulk GaAs. Related studies of ion implantation-induced intermixing in InP/InGaAs quantum well and InGaAs/GaAs quantum dot structures further revealed that the degree of intermixing/interdiffusion was influenced by the surface capping layer. The use of other capping layer treatments with a wide range of thermal expansion coefficients were also shown to influence the luminescence emission, providing strong evidence that stress plays a major role in controlling interdiffusion in these systems.

PhD student, Christine Carmody, working with the high energy ion implanter

Anodic Oxidation

Anodic oxidation of Al creates an oxide layer that is characterised by a hexagonally close-packed ordered array of pores with nanometer dimensions, the size and density of which can be controlled by changing the anodising conditions and pre/post-anodising treatment. Interest in porous alumina has increased recently due to its potential as a template for the synthesis of nano-sized materials. The simplicity of the electrochemical fabrication process only serves to increase this appeal. Work is currently being undertaken to maximise pore ordering in systems consisting of Al layers deposited on semiconductor substrates, as well as investigating avenues for the use of alumina as a template for the growth of semiconductor nanostructures.

Mechano-Thermal Processing of C and BN Nanotubes

Significant progress has been made in the synthesis of C and BN nanotubes using the mechano-thermal process, which consists of high-energy ball milling and thermal annealing. This includes an improved understanding of the formation mechanism for C nanotubes and a significant improvement in the control of the size and structure of BN nanotubes. In the former case, mechanical grinding of graphite creates a precursor for nanotube growth with subsequent annealing activating the growth of two types of multi-walled nanotubes, thin nanotubes (diameter <20 nm) which are formed via crystallisation of disordered carbon, and thick nanotubes (diameter >20 nm), which are formed through a metal catalytic solution-precipitation process. In the latter case, annealing conditions and specific catalysts were used to control the growth of BN nanostructures. This enabled the growth of BN nanotubes with diameters as small as two atomic layers at low temperatures where thick nanotubes are prevented from forming. It was also found that BN nanotubes with novel shapes and structures (bamboo or cone) could be prepared for special applications.

Ion Beam Modification of Materials

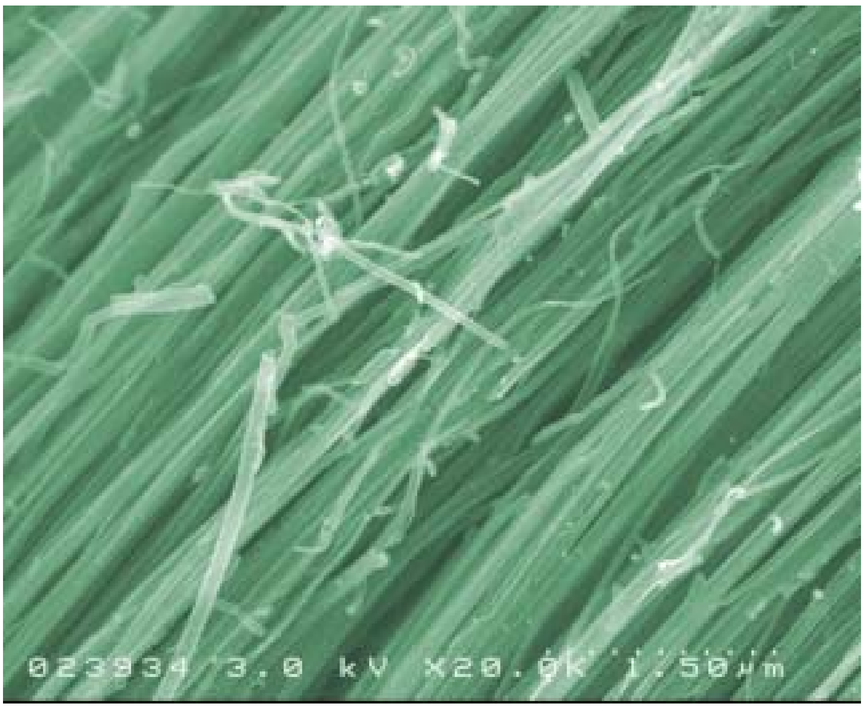
Radiation Damage

With the ever increasing scale of device integration, and the widespread use of ion-implantation as a processing tool, the understanding of irradiation-induced defects, their structure, mobility and interactions has become increasingly important. Studies of ion-irradiated silicon using extremely sensitive carrier lifetime measurements have shown that irradiation-induced defects can penetrate well beyond the range of the implanted ions. In contrast, studies of ion-irradiated compound semiconductors, including ZnO, GaAlAs, InP, and SiC, have concentrated on structural changes, including the influence of dynamic annealing on the evolution of disorder, and defect-annealing phenomena.

In a very different study, in-situ transmission electron microscopy was used to explore the effect of ion-irradiation on the structure and evolution of nano-scale cavities (nanocavities) in Si. The nanocavity diameter was found to decrease as a function of ion dose in both the crystalline and amorphous phases and mechanisms for such changes have been investigated. The observed rate of nanocavity diameter decrease, as a function of ion dose, was found to be consistent with a ballistic process.

Implant Isolation

Because of its potential for device applications, irradiation-induced electrical isolation of semiconductors has been studied in several material systems. In one such study, both n- and p-type InGaAs epilayers grown on InP were implanted with H, Li, C and O ions. The thermal stability of the isolation was investigated as a function of annealing temperature with the production of shallow donors in the InP substrate found to be an important factor regulating isolation in this system. Similar experiments conducted on GaAsN layers with different N compositions showed that the isolation process was independent of the N fraction in the layer. The thermal stability of the defects responsible for carrier compensation in GaAsN was also investigated. In the case of ZnO, sheet resistivities were shown to be increased by up to seven orders of magnitude as a result of ion irradiation. However, due to extremely efficient dynamic annealing processes in ZnO, the ion doses needed for isolation of this material were about two orders of magnitude larger than those required doses in GaN. The defect-induced electrical isolation of ZnO was further found to be unstable to rapid thermal annealing at temperatures above ~300°C.



Scanning electron microscopy image of nanotubes synthesised by mechanochemical process

Dr Ying Chen and Dr Jun Yu demonstrate the strength of nanotubes using a model. Nanotubes have many potential applications in structural engineering one of which is sporting equipment such as tennis racquets

Ultrafast Photodetector Materials

Earlier studies examined the effect of ion-implantation on the carrier lifetime in InP. Recent studies have extended these measurements to look at the effect of Fe implantation on carrier lifetimes in InP and InGaAs. Hall effect measurements determined the evolution of electrical characteristics with ion dose and annealing temperature, and double-crystal X-ray diffraction (DCXRD) and transmission electron microscopy (TEM) measurements were used to glean detailed information about damage and strain in the samples. Time resolved photoluminescence measurements, performed by collaborators at the Royal Institute of Technology in Sweden, showed that both implantations of p-InP with P ions and semi-insulating InP with Fe ions could produce a material with sub-picosecond response times.

Si-Based Photonics and Light Emission from Si Nanocrystals

Research has continued into the properties and applications of Si-nanocrystal-based photonic materials and structures with recent studies examining: a) the effect of impurities on the luminescence intensity and lifetime, b) the effect of materials structure on measured luminescence spectra, c) the fabrication and properties of optical waveguides containing Si nanocrystals, and d) the photoresponse of Si nanocrystals and the prospect of optical gain from such materials.

Passsivation and depassivation kinetics were determined by studying the effects of isochronal and isothermal annealing schedules and modeling the results with a generalised reaction rate model. This enabled activation-energy distributions and reaction rates to be determined for both the passivation and depassivation reactions. An important outcome of this study was the fact that there is an optimum passivation annealing temperature, with the efficiency of passivation falling for temperatures above about 500°C due to the increasing significance of the depassivation reaction. The Si nanocrystal luminescence efficiency and spectral distribution were also found to be sensitive to annealing ambient, with significant differences being observed for samples annealed in Ar or N_2, and to the presence of metallic impurities, such as Cu, Au and Fe.

The effect of sample structure on the measured photoluminescence emission from Si nanocrystals, including the role of optical microcavities, was explored. This included studying the effect of simple layered structures, such as single SiO_2 layers grown on Si, as well as deliberately engineered microcavity structures consisting of a nanocrystal-rich layer sandwiched between wavelength-specific Bragg mirrors. The study highlighted the fact that photoluminescence emission spectra can be dramatically influenced by the sample structure, with both the intensity distribution of the excitation source and the spectral distribution of the emitted light being sensitive to such structure.

The optical properties of nanocrystal–containing slab- and rib-waveguide structures were investigated and the structures used to study the prospects for optical gain in such systems. These structures were fabricated either by using plasma-enhanced chemical vapour deposition (PECVD) to grow alternate layers of SiO_2 and silicon-rich oxide (SRO) or by ion-implantation of Si into SiO_2. Nanosecond optical pump-probe measurements were performed by guiding an 800 nm probe beam within the nanocrystal-rich layer and optically pumping the nanocrystals with 25 ns pulses of 355 nm radiation. Initial measurements suggest that induced absorption (pseudo-free carrier absorption) is the dominant mechanism on this time scale.

Materials Processing and Characterisation

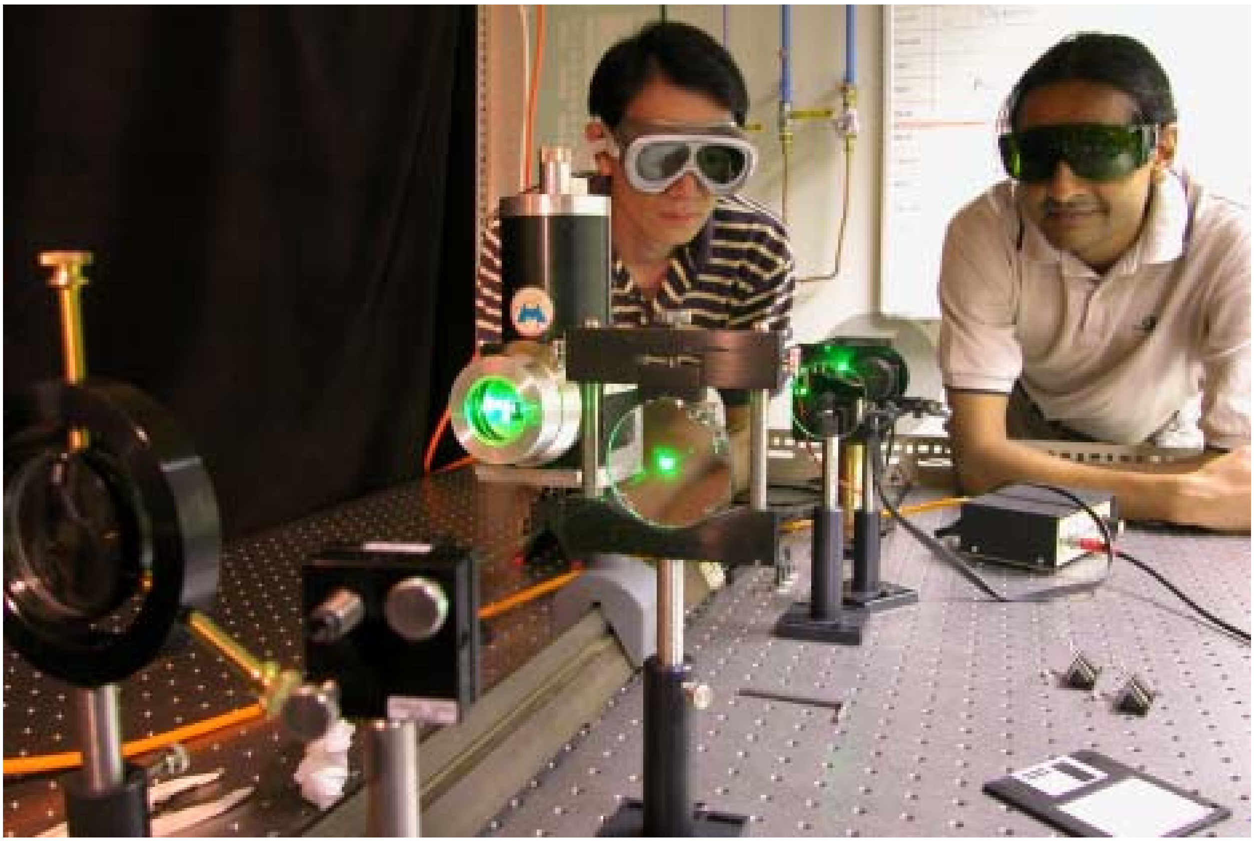
Atomic Scale Structure and Surface Properties

Studies of semiconductor materials, using techniques such as perturbed angular correlation (PAC) and extended X-ray absorption fine structure (EXAFS) provide important insight into atomic-scale phenomena. A broad range of such studies have been undertaken over the past few years, many using international synchrotron facilities. This has included studies of the structure and structural relaxation of amorphous compound semiconductors produced by ion-implantation, which has shown that relaxation proceeds via the annihilation of homopolar bonds, as well as characterisation of semiconductor and metallic nanocrystals embedded in a silica matrix. Structural information is readily apparent from changes in the atomic radial distribution function and can be used to study the effects of the nanometre-size dimensions, strain at the nanocrystal/matrix interface and matrix-induced compression.

A range of complementary characterisation techniques, including EXAFS and PAC, were employed to study the atomic scale structure and mechanisms associated with metallic-impurity gettering mechanisms in Si. The efficiency of implantation-induced nanocavities as gettering sites for Pd impurities was measured as a function of implantation dose and annealing temperature. It was shown that nanocavities effectively trap Pd impurities and an attempt was made to identify the gettering sites and reconstruction processes for Pd impurities on nanocavity inner surfaces.

Work has also continued on the application of synchrotron radiation to the characterisation and modification of compound semiconductor surfaces (GaAs and III-V nitrides). In recent work synchrotron-based high-resolution core-level photoemission and valence-band emission measurements have been used to characterise H chemisorption on non-polar GaAs (110) and polar GaAs (100) and GaAs (001) surfaces. Chemisorbed atomic H forms both Ga-H and As-H bonds on all three surfaces causing chemical shifts of core-level binding energies and changing the valence band emission. For low H exposures, As desorbs from all surfaces. However, at higher exposures, the (110) surface transforms into a Ga-rich structure with traces of metallic Ga, while the (100) surface transforms into an As-rich structure. Additional changes in the binding energy of bulk components of Ga and As core levels have also been observed as a function of H exposure, which were explained by hydrogen-induced changes in band bending.

Below: Panoramic view of the new RBS accelerator labs

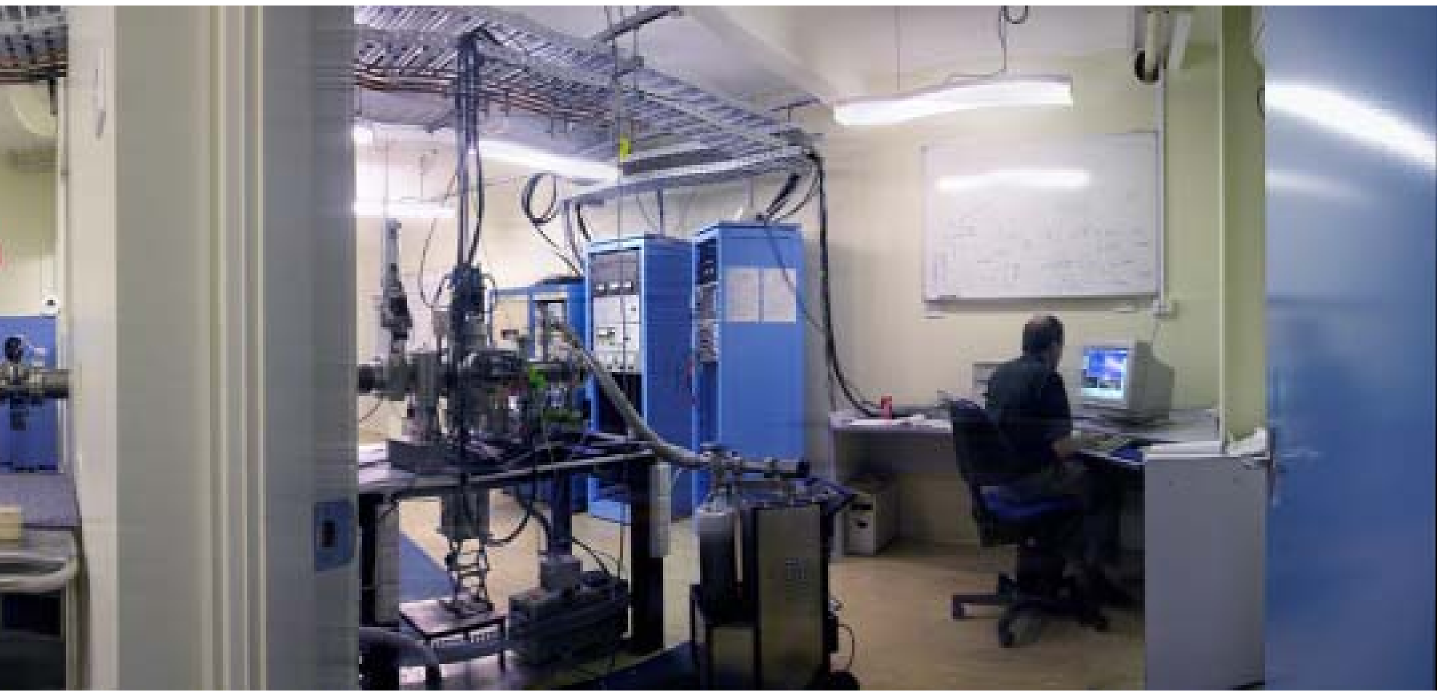


Dr Hoe Tan, ARC QEII Fellow and Dr Sanju Deenapanray, ARC Postdoctoral Fellow, in the optics laboratory

Post-ionisation experiments (the subsequent ionisation of neutral sputtered atoms) using the Free Electron Laser (FEL) at Argonne National Laboratory (ANL) have continued in collaboration with researchers from Newcastle University and ANL. A new analysis chamber and Time-of-Flight Spectrometer were constructed at the FEL facility to undertake the first post-ionisation experiments.

Secondary Ion Mass Spectrometry (SIMS)

Anomalous SIMS broadening of buried delta layers in Si was observed under O beam bombardment at angle of incidence close to 30˚. Channelling effects have been proposed as a possible explanation for the effect with simulations using the Marlowe program revealing a channel in Si (100) at slightly higher impact angle (35˚), while one weaker channel opens at



Victoria Coleman, PhD student, loading samples into the MOCVD reactor

55°. Careful SIMS measurements showed an additional small enhancement in broadening around 50° and experiments are now under way to explain this difference between simulation and experiment.

Microindentation and Mechanical Properties of Semiconductors

A comprehensive understanding of microindentation behaviour in a wide range of semiconductors has been obtained using a number of analytical techniques.

A particular highlight of research in 2002 was the use of in-situ electrical measurements to probe indentation-induced phase transformations in amorphous-crystalline Si structures.

Dramatic differences were observed between the deformation behaviour of relaxed and unrelaxed amorphous Si.

The former undergoes an amorphous-to-crystalline transformation on loading and can transform back to amorphous Si during some unloading conditions.

In comparison, unrelaxed amorphous Si deforms plastically under indentation and remains in the amorphous phase.

These intriguing, room temperature crystalline-to-amorphous and amorphous-to-crystalline transformations have been examined by ex-situ microscopy techniques.

Optoelectronic Devices and Integration

Preliminary work carried out in the growth of InP-based vertical-cavity surface emitting lasers (VCSELs) has been very encouraging. We have grown InP-AlGaInAs multilayers as the Bragg mirror due to the large refractive index difference between these two materials. By growing only 25 pairs, reflectivity in excess of 99% was achieved. Work is now in progress to grow the full VCSEL structure and fabricate and characterise these devices for 1.55 µm applications.

The use of Selective Area Epitaxy (SAE) was also investigated for the growth of quantum well structures. Patterning the substrates with oxide masks prior to growth enables tailoring of growth rates and compositions in the 'window' region. This has particular advantages for the integration of optoelectronic structures. GaAs has been grown with a growth rate enhancement of up to 1.4, yielding excellent quality material. InGaP (lattice-matched to GaAs) has also been grown with minimal ordering and growth rate enhancements exceeding a factor of two. InGaAs/GaAs quantum wells with emission differences of up to 90 nm between different parts of the wafer was achieved.

Impurity-free intermixing of quantum-well laser diode structures for optoelectronic integration was studied. It was found that when dielectric cap layers are used in order to promote intermixing, the intermixing process is accompanied by a significant Zn migration from the highly-doped regions of the device into unintentionally doped regions. This adversely affects the laser performance. To achieve high device performance for optoelectronic integration, a good option would be to replace the commonly used Zn with C as the p-type dopant. Carbon is stable upon annealing at temperatures higher than 900°C. However, the role of different point defects in the intermixing process of laser diode structures needs to be further investigated, since C doping occurs by replacing a group V atom in the GaAs lattice, and not a group III atom, as is the case for Zn.

The influence of the thickness of the SiO_2 layer used as an insulator outside the ridge in high power 980 nm laser diodes was thoroughly investigated. It was found that the extra absorption that is provided by the extension of the optical field into the lossy Ti/Pt/Au metallisation gives selective absorption for the first-order lateral mode and thus improves the kink-free power output by 30-50%.

Quantum dot infrared photodetectors (QDIPs) with a 30-stacked-layer InAs/GaAs quantum dots grown by molecular beam epitaxy have shown good device performance. High temperature annealing of QDIPs led to strain relaxation. Strain compensating QDIPs are under investigation.

Other Areas

Within the acoustics area, there is a major continuing ARC-funded cooperative project with the University of NSW and Melbourne University on the acoustics of the didjeridu — there is much interest in this instrument from musicologists around the world and it seems important that basic understanding be developed in Australia. There have also been some more applied interactions on microphone design and related subjects with CSIRO and industry, and in addition there are currently research interactions with several biologists on hearing and sound production in humans and other animals.

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Martin Conway
Antony Williams (until March)

Departmental Administrator
Laura Walmsley (until October)

Laser Physics Centre

Professor Barry Luther-Davies - Head of Laser Physics Centre

The Laser Physics Centre is engaged in laser-based research on topics spanning fundamental and applied physics and engineering.

http://laserspark.anu.edu.au

Introduction

Research within the Centre covers many of the most exciting aspects of contemporary laser-based research. The Centre has strong programs on optical solitons; quantum computing; laser cooling and trapping of atoms; optical materials; and photonics, to mention just a few. Research in photonics is partly supported by the Australian Photonics Cooperative Research Centre, and Professor Luther-Davies remains a Director of that Centre.

This year several members of the Centre worked on a contract to assist RPO Pty Ltd, a spin-off company from the Laser Physics Centre, which has its operations on the ANU campus. RPO makes photonic "chips" using proprietary Inorganic Polymer Glasses (IPG™) originally developed in the Laser Physics Centre. RPO has made excellent technical progress during the year and has employed new staff including Ben Cornish, Graham Gordon and Maureen Brauers. Reiner Friedrich and Dr Anke Freydank returned to Germany in September to undertake research at Potsdam University funded by the Australia-Germany exchange agreement. Unfortunately they are unable to return to Canberra to complete their appointment. Dr Max Lederer, a valued member of our photonics team also left late in the year to join a laser company in Austria. Dr Olivier Uteza, an IREX Fellow from the Lasers, Plasmas and Photonic Processes Laboratory at the Aix-Marseille II University, France, completed his Fellowship in June. He was involved in the research of femtosecond laser induced order-disorder phase transitions with Andrei Rode and Eugene Gamaly.

The Centre congratulates two members of its academic staff on their promotion to level D: Dr Marek Samoc and Dr Andrei Rode; and Dr Wieslaw Krolikowski for his appointment to a continuing position. On general staff matters, Renee Vercoe took over as Departmental Administrator from Kristina Milas during the year whilst Craig McLeod took an extended period of leave to work in Canada for a year.

The activites within the Centre can be broadly divided into seven areas: Laser Matter Interactions, Nonlinear Optical Phenomena, Nonlinear Optical Material development, Solid State Spectroscopy, UV Spectroscopy, Atom Manipulation, and Photonics.

Laser-Matter Interaction Physics

Ultra-Fast Pulsed Laser Deposition (UFPLD) is a process patented by ANU researchers that allows the deposition of exceptional quality thin films or novel nano-structured materials by evaporating solids into either high vacuum or an inert gas using short laser pulses. UFPLD can be optimised for efficient evaporation of almost any solid, but the laser parameters required are beyond those available from commercial systems. As a result the UFPLD project involves both the development of special laser systems for UFPLD, and application of UFPLD to the production of novel materials.

Laser Hardware

Good progress has been made towards the creation of an optimised laser system for UFPLD based on a very low repetition rate (down to 1.5 MHz) mode-locked Nd:YVO_4 laser oscillator and a power amplifier. High-modulation 15-quantum-well InGaAs semiconductor saturable absorber mirrors (SESAMs) have been developed to produce stable passive mode-locking. The very low mode-locking frequencies require an exceptionally long optical resonator and a novel "zero-q-transforming" multi-pass cell was used to provide a variable cavity length up to 100 m long. Currently, the laser oscillator operates at three different repetition rates: 4.1 MHz, 2.6 MHz and 1.5 MHz, output pulses of 13-ps duration, and an average power up to 4 W in a diffraction-limited beam (M^2<1.1). A double pass Nd:YVO_4 amplifier was developed to increase the output power up to 10 W. Frequency conversion to 532 nm with an efficiency >80% was achieved using an external non-critically phase-matched LBO frequency doubler.

This laser has been used to deposit chalcogenide glass (As_2S_3 and $Ge_{33}As_{12}Se_{55}$) films and obtained a three-fold increase in the deposition rate compared to our previous work. This demonstrates that UFPLD can deposit thin films for important technological applications at rates relevant to industrial processes. In collaboration with the Fraunhofer Institute of Laser Technology in Aachen, Germany, a higher-power amplifier to increase the laser power to >40 W is being implemented. This system will allow evaporation of the most challenging materials such as Si or highly reflecting metals.

Magnetic Carbon Nano-Foam

It was reported earlier that the evaporation of C into an Ar atmosphere using UFPLD leads to the production of an unusual magnetic C nano-foam. This year a thorough study of ferromagnetism in these materials was performed indicating a very high density of unpaired spins – up to 1.51×10^{20} per gram. The saturation mass magnetisation of the foam is several times higher than any previously observed all-carbon system. The nano-foam has been shown to be a soft ferromagnetic semiconductor with a narrow hysteresis curve and a Curie temperature exceeding 90 K. This unexpected behaviour, as we have shown, can be quantitatively interpreted using spin-polarised *ab initio* calculations. The results suggest that unpaired spins are introduced by sterically protected carbon radicals, which are immobilised in the non-alternant aromatic system of C sheets with negative Gaussian curvature (so called schwarzites).

BN Nano-Clusters Produced by High-Repetition-Rate Laser Ablation

We synthesised Boron Nitride (BN) nanomaterial *via* UFPLD of a BN target in nitrogen gas. The material was microscopically and chemically analysed by high-resolution transmission electron microscopy; electron energy loss spectroscopy; electron diffraction; and energy-filtered TEM. Nano-rods, multi-layered nano-cages, double-layered "nano-horns", and multi- and particularly single-walled BN nano-tubes, which are extremely rare in BN-nano-structures produced by other means, were discovered in the product. BN nano-tubes with various diameters and number of layers, including single-walled nano-tubes, were frequently found assembled as "ropes".

Laser Induced Phase Transitions

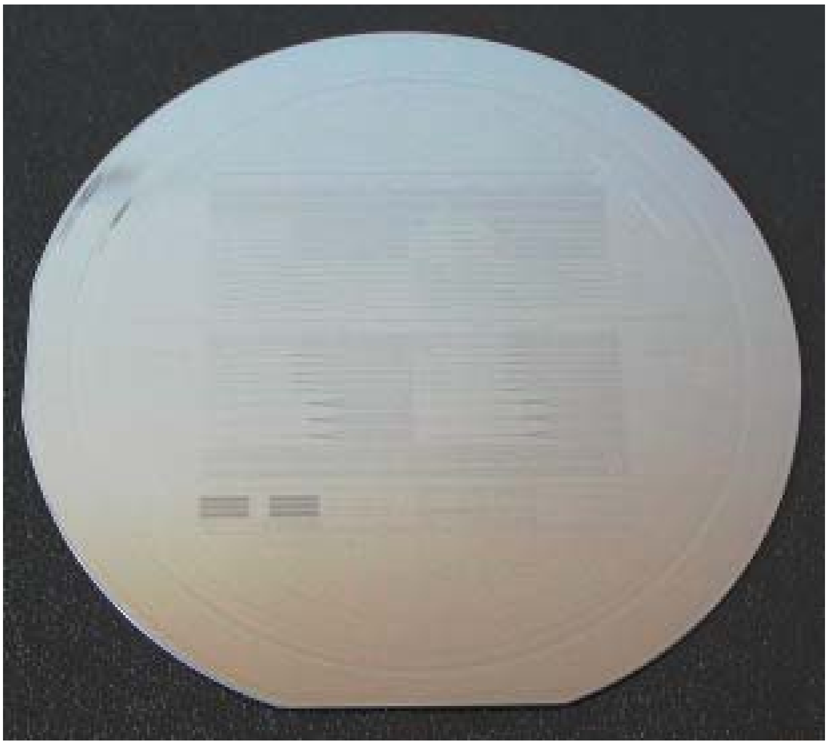
Order-disorder phase transitions induced by femtosecond laser irradiation of G films have been studied using a pump-probe technique with a record 200-fs time resolution. The data obtained allowed us to derive numerically the temporal evolution of the real and imaginary parts of the dielectric function. The time history of the phase transition induced by the femtosecond laser is fully reconstructed at the picosecond time scale and the nanometer space scale on the basis of the experimental data.

The analysis shows that the first sharp reflectivity rise in a few ps after the excitation coincides with the time required for the transition to a new phase when the heat conduction is negligible, while the second stage of slow change, ~100 ps, is dominated by the heat transfer. It appears that the recovered electron-phonon collision rate and heat conduction coefficients are transient non-linear functions of temperature. The spatial (nanometer-scale) and temporal (picosecond-scale) constraints are dominant in the course of the phase transition that makes it drastically different from the phase transform in a bulk solid in conditions of thermodynamic equilibrium. A comprehensive analysis leads to a proper control of the evolution over the optical properties related to the reversible phase transition in the material induced by the femtosecond laser.

Nonlinear Optical Phenomena

Optical Solitons in Saturable Nonlinear Media

Certain materials modify their optical properties, such as index of refraction, when illuminated by light of sufficiently high intensity. These so called nonlinear media can be used to observe a variety of effects induced by propagating light beams, and in particular formation of spatial solitons. A spatial optical soliton represents an optical beam that propagates in a nonlinear medium without changing its shape. The process of diffraction is prevented by the self-induced change of the refractive index. Spatial solitons are of special interest for applications in all-optical switching or processing. We have studied theoretically and experimentally the formation and interaction of various types of spatial optical solitons in optical systems. We have shown the possibility of formation of complex objects consisting of several mutually trapped higher order soliton beams. We have demonstrated this effect experimentally using photorefractive nonlinear crystals and have observed stable



IPG™ polymer wafer with characterizing structures propagation and collisions of three-component vector dipole solitons.

Optical Beams in Nonlocal Nonlinear Media

In another study we investigated theoretically the propagation of solitons in nonlocal nonlinear media where the intensity of a wave (or a beam) at a particular point affects not only the medium at that very point but also the surrounding region. Some important examples of such media include plasmas with non-locality caused by thermal effects, and a Bose-Einstein condensate where non-locality is due to the finite-range of particle interactions. We proved that nonlocality suppresses the instability of wave fronts, prevents the collapse of finite beams and leads to the formation of stable multi-dimensional solitons.

Localisation of Light in Optically-Induced Periodic Structures

The propagation of light beams in a medium whose refractive index varies periodically in space leads to many interesting effects such as discrete diffraction and the appearance of band gaps where the propagation of light is forbidden. We have investigated theoretically and experimentally the propagation of beams in photorefractive crystals containing optically induced index gratings. We showed that the optical beams created various types of localised structures (discrete solitons) when propagation occurs in the presence of nonlinearity.

Nonlinear Optical Materials

Development of new, more efficient nonlinear optical materials, optimised for particular applications in photonic technologies, remains one of the important goals of research in modern optical sciences. LPC researchers have been focusing on both the theoretical understanding of factors influencing microscopic and macroscopic optical nonlinearities and on development of several classes of nonlinear materials, including polymers and glasses suitable for use in waveguide devices.

Nonlinear Properties of Model Molecules and Polymers

Third-order nonlinear optical properties of various organic and organometallic materials were studied to establish structure-property relations to guide the design of high nonlinearity materials for photonics.

A particular focus has been electro-chromic switching of the third-order optical nonlinearity in organometallics, including dendritic structures. We had previously discovered that it is possible to switch the sign of the absorptive and refractive nonlinearities of certain organometallic molecules at 800 nm by electron transfer from an electrode. This study has now been expanded to the longer wavelength region important for telecommunications applications.

Optical Nonlinearity of Chalcogenide Glasses

We have used our tunable fsec optical parametric generator to measure the dispersion of the optical nonlinearity of chalcogenide glasses. The nonlinearity of As-S-Se glasses was found to be enhanced at particular Se concentrations in agreement with earlier work. The glasses had excellent nonlinear figures of merit for optical switching and useful nonlinearities ($\approx 10^{-13}$ cm^2/W). The Verdet constants for these materials were also determined and indicated it should be possible to make chip sized magneto-optic devices in chalcogenide glass.

Nonlinear Optical Chromophores for Polymer Optical Fibres

By incorporating a nonlinear optical chromophore inside the core of an optical fibre, enhanced nonlinear response is expected both because of confinement of the optical field and enhanced interaction lengths. Our interest in chromophores suitable for inclusion in polymer fibre cores has been motivated by an industry-sponsored project to develop an electro-optic fibre for voltage sensing.

We have synthesised soluble derivatives of π-conjugated distyrylbenzene: an oligomer of *p*-phenylenevinylene asymmetrically substituted in the *para* position with electron donating alkyleneoxy group bearing the methacrylic group, and an electron accepting alkylsulphonyl group bearing alkyl chains of different length (MTPV-ORSO, MTPV-SOHE). The molecular second-order and third-order nonlinearities were estimated with quantum chemical calculations (MOPAC). The methylmethacrylate side-chain copolymer (MTPV-ORSO-MMA) could be incorporated into the core of the fibre perform and used to create a single mode polymer fibre.

The nonlinear optical properties of the polymer materials containing the new chromophores were measured with several techniques including second harmonic generation induced by corona poling to determine the second-order nonlinearity and degenerate four-wave mixing to determine the third-order nonlinearity

A comparative study of the molecular second hyperpolarisability was performed for the conjugated molecules of MTPV-SOHE and *p*-bis(o-methylstyryl)-benzene (Bis-MSB). The asymmetric substitution causes a red shift (24 nm) of the absorption maximum and enhancement of third-order optical susceptibility. The second hyperpolarisability of MTPV-SOHE was about six times bigger than that in Bis-MSB.

Solid State Spectroscopy

Quantum Computing

The concept of a quantum computer emerges from the realisation that the laws of quantum mechanics sets the ultimate lower limit for the resources required to perform any calculation. If a computer can be built whose operation fully utilises the laws of quantum mechanics, it is predicted that it will be exponentially faster, for a range of important algorithms, than its classical counterparts.

The Solid-State Spectroscopy Group is developing quantum computer architectures based on nuclear/electron spins that are associated with optically active centres. This allows the spins to be manipulated and measured using purely optical techniques. The use of optical centres neatly sidesteps many of the problems found in other architectures. Two types of centres are currently being investigated, rare-earth ions doped in insulating crystals and colour centres, particularly the nitrogen-vacancy centre in diamond.

Work is being undertaken to determine the feasibility of a quantum computer based on rare-earth doped crystals. The study is concentrating on Eu and Pr doped Y_2SiO_5. This year single qubit gate operations were demonstrated and characterised using quantum state tomography. Fidelities of greater than 90% for the combined preparation and measurement process were achieved. The electric dipole-dipole interactions required for multiple qubit operations were also measured. These results confirm that our existing experimental system can access the parameter space necessary for two qubit operations.

Up until now a major argument against using rare-earth doped crystals for quantum computing was the relative short coherence times of their nuclear spin states. We have developed a new method for extending these coherence times. In the first demonstration of this technique, the nuclear spin coherence time of $Y_2SiO_5:Pr^{3+}$ was increased from 0.5 ms to 81 ms. In related work, the robustness of the spin coherence to optical perturbations was also investigated using Raman and Raman heterodyne techniques.

The application of the nitrogen-vacancy centre in diamond for various quantum computing functions is being investigated. A promising application is the use of the centre as a single electron spin detector. The concept is to transfer the spin of the centre to be measured onto the electron spin of the N-V centre and then to optically readout the N-V spin state. In this way the spin state of non-optically active centers can be determined. The theoretical analysis of this technique has been completed and, in collaboration with DSTO, a confocal microscope system is being developed to perform single site spectroscope experiments. Measurements on bulk diamond samples were undertaken to establish the relevant dynamical properties of the N-V centre, in particular the dynamics of the optically induced spin polarisation. Associated fundamental studies investigating perturbation of electromagnetic induced transparencies due to auxiliary driving fields were performed using the nitrogen-vacancy centre.

Optical Signal Processing

The intermediate goal of this project, funded by DSTO and the Australian Photonics Cooperative Research Centre, is to develop a microwave spectrum analyser for radar and communication applications. The analyser which utilises the long optical coherence times of rare-earth doped crystals has the unique feature of being able to perform real time spectral analysis of all frequencies over a potential bandwidth of 10 GHz. In this application, a spectral grating is stored across an inhomogeneous broadened infrared absorption line, which is used to scatter a beam modulated by the unknown microwave frequency. The time dependence of the scattered beam indicates the spectrum of the microwave source. Operation at 1.54 μm, corresponding to the $I_{15/2} \Leftrightarrow I_{13/2}$ absorption line in Er doped Y_2SiO_5, allows us to capitalise on technology developed for optical communications.

The electron spin resonance and Raman heterodyne techniques have been employed to study the structure and dynamics of the electron spin states of the Er site. The results of this work are to be used to develop techniques to reduce the optical dephasing of the $I_{15/2} \Leftrightarrow I_{13/2}$ transition, a critical parameter for the spectrum analyser's operation.

Joanne Harrison working on the electron paramagnetic resonance equipment

UV Laser Spectroscopy

The work in this laboratory is aimed at developing and applying high resolution laser and nonlinear optical techniques for the study of molecules of atmospheric and environmental interest in the vacuum ultraviolet region (below 200 nm). This year, a new high resolution laser source based around a periodically poled KTP crystal in a ring-cavity optical parametric oscillator (OPO) has been developed and characterised. The OPO is injection seeded by a cw diode laser, and pumped by a frequency-doubled single-longitudinal mode Nd:YAG laser.

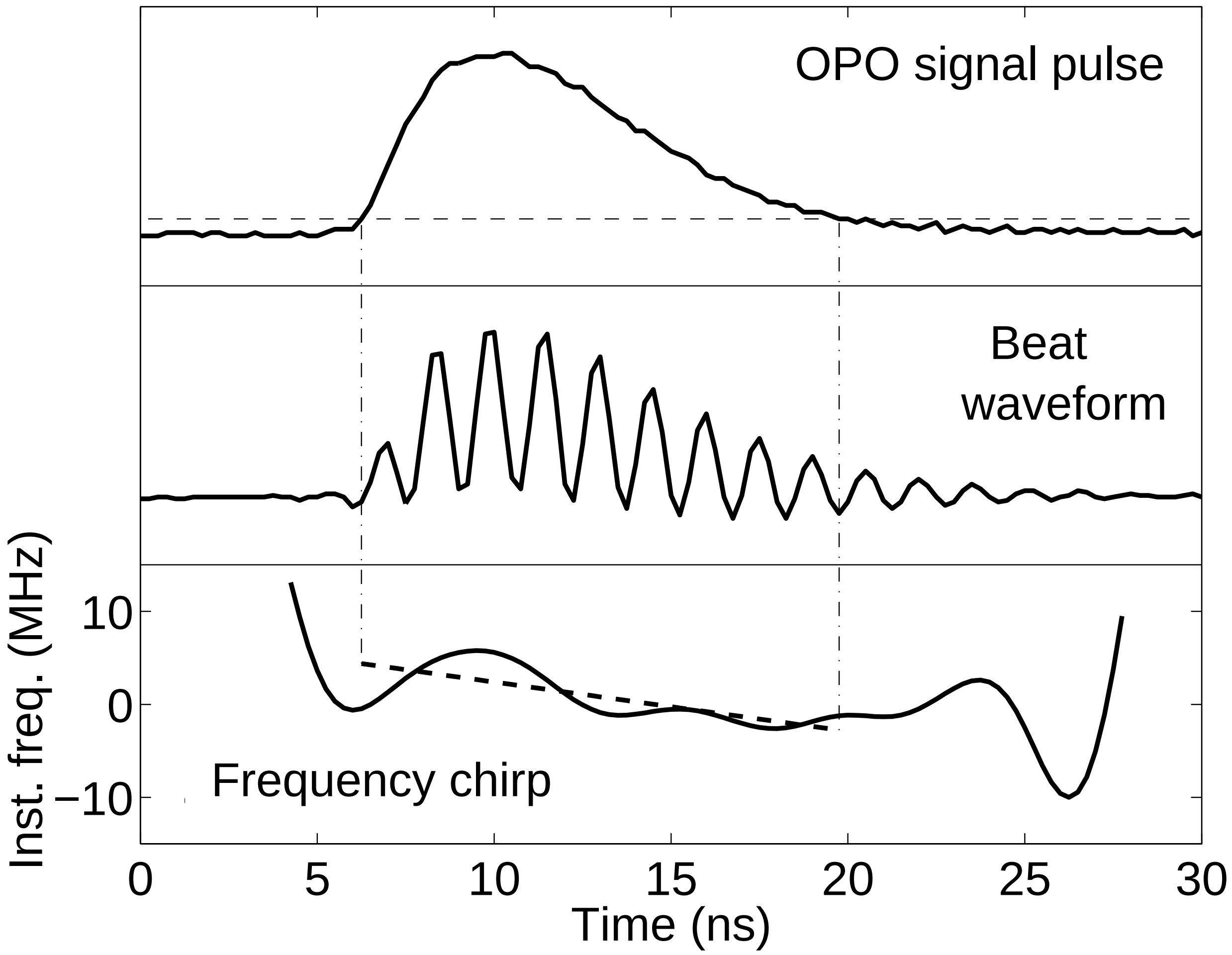
The figure below shows how the optical phase measurements can be used to reconstruct the frequency chirp in the OPO output that arises from phase mismatch and self-phase modulation. The frequency excursions were found to be reproducible, and less than the Fourier transform limit of the pulse duration, making the OPO a promising source for high resolution spectroscopy. Ways to reduce both the frequency chirp and the pulse-to-pulse frequency jitter in the OPO output have been implemented, as a prelude to amplification and upconversion to a wavelength of ~120 nm for high-resolution vacuum-ultraviolet spectroscopy.

Atom Manipulation

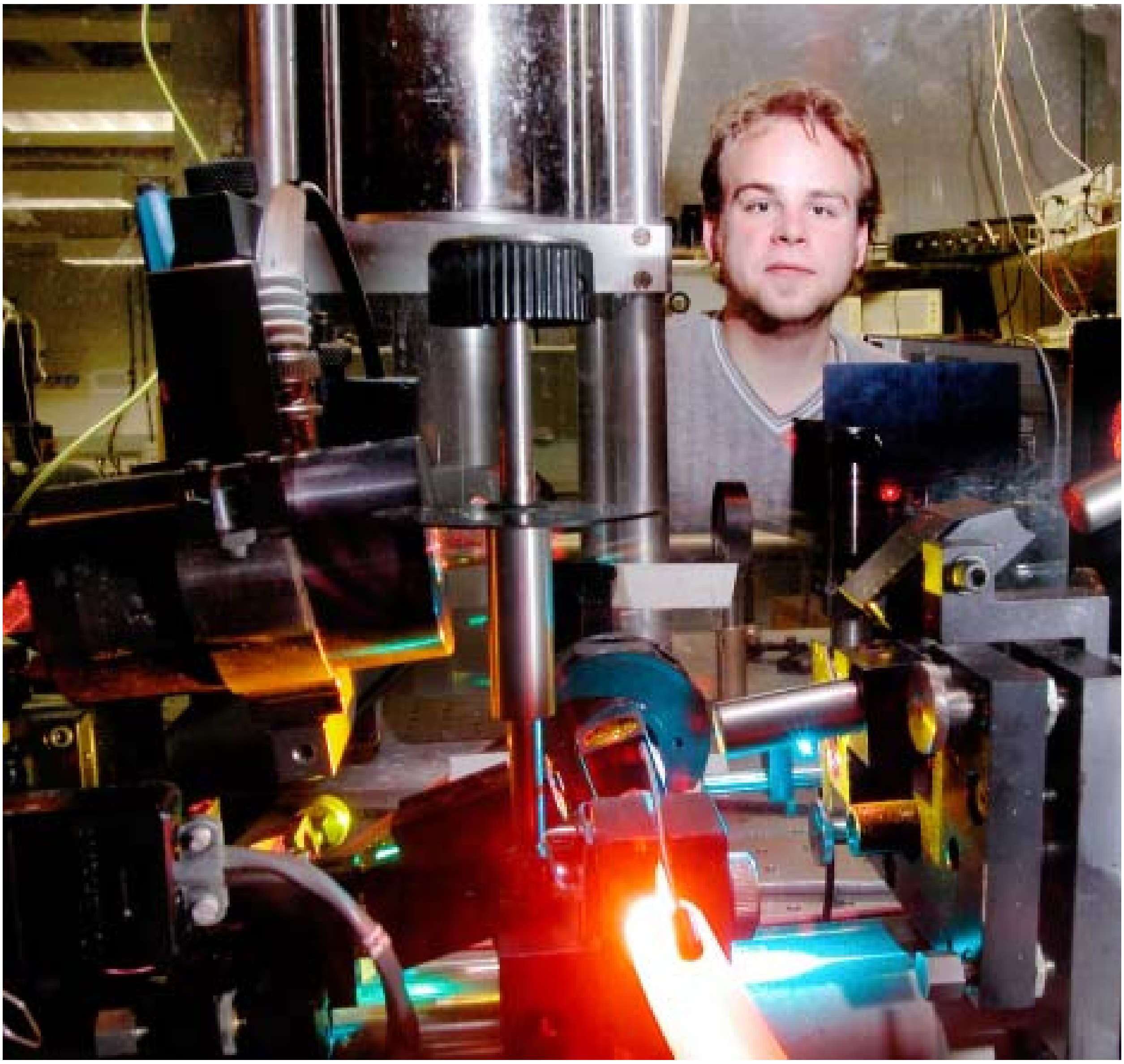
The Atom Manipulation project is a joint program between the Laser Physics Centre and the Atomic and Molecular Physics Laboratories (AMPL) which uses laser cooling and trapping techniques for atom optics and atomic collision physics experiments.

Significant improvements to the metastable helium magneto optic trap (MOT) have been implemented this year, which have increased both the number of trapped atoms, and the sensitivity of detection using both atomic fluorescence and electron multiplier techniques. The atom trap now has a maximum of ~2 x 10^9 atoms at 1 mK (~3 x 10^8 after optical molasses cooling to 250 μK), and the trap diameter is now ~5 mm yielding a peak density of ~10^9 atoms/cm^3.

The improvements have been due to an increase in the capture velocity to ~80 m/s and the introduction of a quasi-dark spot MOT. This has been achieved through implementation of a higher magnetic field gradient using an optimised coil design, together with the introduction of a fibre laser enabling larger laser beam diameters. In addition, the magnetic coil switch-off time can be reduced to <300 μs using a novel circuit design to provide a higher duty cycle for experiments.



Beat signal (top), with reconstructed OPO temporal pulse (centre) and instantaneous-frequency curve (bottom) following Fourier transformation



Elliot Fraval making adjustments to the ultra-high resolution ring laser

Photonics

Inorganic Polymer Glasses

With support from the Australian Photonics CRC, we have continued to develop novel organic-inorganic polymer glasses IPG™ for the fabrication of optical chips. Following the transfer our earlier poly-siloxane materials to a spin-off company, RPO Pty Ltd, research has focused on the synthesis of new photo-patternable polysiloxanes with reduced optical loss and improved physical properties. We have developed a new approach to the synthesis of silica-zirconia based IPGs that allows reduction in the OH absorption compared with previous methods.

Because of growing interest in electro-optic polymers, we are working to incorporate electro-optic chromophores into IPG™ materials. Several new donor-bridge-acceptor three-ring acetylenes have been synthesized, employing the diethylene glycol group as the donor, the fluoro substituents and the 2-ethylhexylsulfonyl group as the acceptor. Compared with previous chromophores, the optical loss in the CH overtone region is dramatically decreased due to replacement of hydrogen with fluorine and the replacement of the CH double bonds with C-C triple bonds.

Synthesis of a push-pull disperse red type molecule bearing a methyl methacrylate group on one side and an alkoxy silane group on the other side of the molecule was continued. The attachment of the siloxane group offers the possibility to incorporate the organic molecule into the IPG™ matrix. This work was carried out in collaboration with the group of Dr Mark Humphrey in the Department of Chemistry.

Photonic Modelling and Design

A range of optical waveguide devices for RPO Pty Ltd have been designed. Of particular interest have been designs for particular functionalities which are insensitive to manufacturing tolerances. In addition, we have investigated the use of segmented waveguides to produce up and down tapers to enhance coupling between the waveguide chips and an optical fibre.

Optical Sources

We have continued the development of psec neodymium lasers passively mode-locked using ion implanted, MOCVD grown, Semiconductor Saturable Absorber Mirrors (ii-SESAMs). Long cavity mode-locked lasers producing modest average powers (≈1 W) have sufficiently high peak power to allow efficient conversion to new wavelengths via nonlinear processes. A versatile 20 MHz repetition rate Nd:YVO_4 laser producing ≈1.1 W was shown to produce up to 200 mW of 265 nm light by frequency quadrupling. The same laser has been used to sub-harmonically pump a KTP optical parametric oscillator producing >200 mW of average power at 1573 nm of use for testing telecommunications devices.

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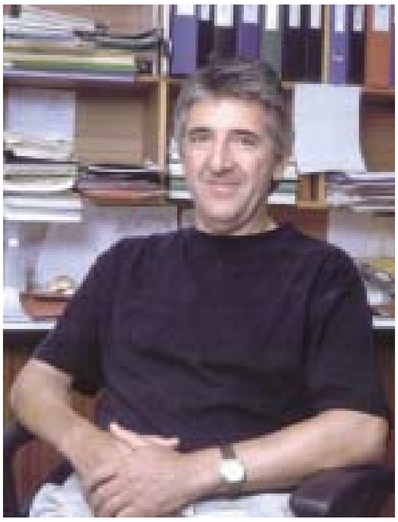
Nuclear Physics



Professor George Dracoulis
- Head of Nuclear Physics

The Department operates the premier laboratory in Australia for accelerator-based research in nuclear physics, providing and developing facilities for local staff and national and international outside users. The facilities are used for postgraduate and postdoctoral training over a wide range of research, from basic to applied.

http://wwwrsphysse.anu.edu.au/nuclear

The Department of Nuclear Physics carries out a broad range of research, ranging from fundamental studies of the nucleus to the development and application of techniques for environmental science and the characterisation of new materials. Many of these exploit the unique capabilities of the Heavy Ion Accelerator Facility and its associated instrumentation.

The research program currently includes:

- Fusion and Fission Dynamics with Heavy Ions
- Nuclear Spectroscopy
- Nuclear Moments and Hyperfine Fields
- Perturbed Angular Correlations and Hyperfine Interactions applied to Materials
- Heavy Ion Elastic Recoil Detection Analysis (ERDA)
- Accelerator Mass Spectrometry (AMS)

Much of the research is collaborative involving other departments, research schools, universities and institutions. This year, extensive use of the facilities was again made by outside users including UK scientists who have formal access through the ANU-EPSRC agreement. Collaborations with outside groups and experiments at overseas facilities are also used by the various research groups to complement the local program.

The general research capabilities of the Department have been enhanced with the completion of a flexible data acquisition system capable of handling larger multiple-element high-resolution detector arrays and high count rates. In the fission-fusion area, development of the fusion product separator *SOLITAIRE* has continued with first experiments scheduled for early 2003. In spectroscopy, augmentation of the γ-ray array *CAESAR* is nearing completion following supplementary funding from the University's Major Equipment Committee, and new instrumentation for nuclear moments and hyperfine field measurements is being assembled, supported by an ARC RIEF grant. Support for a number of the Department's activities including the fission/fusion studies, the spectroscopy of metastable states and applications of Accelerator Mass Spectrometry have been won through applications to the ARC Discovery program, with funding beginning in 2003.

Maintenance and development of the accelerator facility itself is a continuing process and an integral part of the Department's research, with a demand from users for a broad range of energetic beams with precise energy and timing characteristics. Re-plating of LINAC resonators with the aim of increasing the high-field limits has continued, with a parallel investigation of plating techniques resulting in the successful development of a superior procedure for the plating of Pb-Sn superconducting surfaces. A new three-stub resonator has also been designed and a model tested that demonstrates large separation between accelerating and non-accelerating modes. A feature of the design is the significant reduction of demountable joint losses. Exploitation of multi-stub resonators could provide a convenient means of extending the mass range of beams accelerated by the LINAC to mass-100, a prospect to be pursued through applications to the ARC.

Following funding from the Institute Planning Committee the activities of the Accelerator Mass Spectrometry Group have been expanded and more closely aligned with environmental studies. Restructuring of the accelerator building to meet the increasing demands for AMS sample preparation, funded through the University's Capital Management Plan was also completed. The most recent staff change in this area was the appointment of a joint RSPhysSE/RSES Fellow (Dr M.T. Esat). Other staff changes in the Department include the departure of Dr R.A. Bark who is joining the iThemba Laboratories (formerly the National Accelerator Centre) in South Africa and the appointment of Dr M. Dasgupta to a standard position, commencing in June 2003.

Dr G.J. Lane will take up an ARC Fellowship in January 2003, based in this Department. Dr I.I. Gontchar has completed his term as a visitor /research fellow with the Fission/Fusion Group while two visitors to the Spectroscopy Group, Professor C-B. Moon (Hoseo University) and Professor C. Günther (University of Bonn) have also returned to their home institutions. Professor M.N. Rao from Sao Paolo spent most of the year with the PAC experimental group and Dr A. Mukerjee and Dr L. Wacker completed their postdoctoral fellowships with the Fission-Fusion and AMS Groups.

Research Summary

A number of long-term research projects in the area of Fission and Fusion Dynamics with Heavy Ions have been brought to fruition this year. In the process, three research strands, namely the experimental studies of fusion barrier distributions, fission and quasi-fission, and the break-up of weakly-bound nuclei, have been linked with the demonstration that the understanding of their inter-relationship can be exploited for the understanding of nuclear collisions as a whole.

The new approach developed by the Group to study the competition between nuclear fusion and quasi-fission (Nature 2001), and demonstrated for the case of ^{216}Ra, has been applied to a heavier nucleus, ^{220}Th. Measurements from other laboratories with projectiles ranging from ^{40}Ar to ^{124}Sn exist for this case hence measurements for the fusion of ^{16}O with ^{204}Pb have been made to complement the set. Comparison of the cross-sections shows that fusion with the heavier projectiles is suppressed by quasi-fission, typically by a factor of 10, even at energies well above the respective fusion barriers. This result (published in Physical Review Letters) completely overturns previous assumptions, and throws into doubt the “extra-push” model framework commonly used to interpret quasi-fission. Another series of reactions, forming ^{202}Po, have commenced and preliminary results suggest that conventional expectations will be proven again to be incorrect.

In other detailed measurements the Group has shown that the deformation-aligned nuclear ground-state spin has a large effect on fission angular distributions. The data are well reproduced by newly developed computer codes which can also be used to predict the effects on quasi-fission. A comparison with recent precision measurements of quasi-fission promises to test the understanding of the competition between quasi-fission and fusion in reactions involving statically-deformed nuclei.

Several different studies of the break-up of weakly-bound nuclei have contributed to the development of a consistent understanding of the effect of projectile break-up on fusion. One showed that break-up suppresses complete fusion substantially for ^{6}Li- and ^{7}Li-induced reactions on ^{209}Bi, and demonstrated quantitatively the importance of modelling post break-up fragment trajectories (a collaborative study with Dr K. Hagino, Kyoto). Another confirmed experimentally that there is, in contrast, no significant effect of break-up for ^{7}Li incident on the light nucleus, ^{12}C. A third has led to a new approach allowing a link to be made between sub-barrier break-up probabilities and fusion suppression at above-barrier energies. This work (published in Physical Review Letters) shows that break-up principally occurs close to the nuclear surface and that a difference in fusion suppression for light and heavy target nuclei is expected, giving a quantitative explanation for the apparently contradictory results described above.

Dr Gontchar’s theoretical study, aimed at a more complete understanding of fusion barrier energies and barrier distributions, was able to elucidate subtle geometrical effects in the fusion of deformed nuclei. A double-folding model capable of describing the fusion of both spherical and deformed nuclei was also developed.

In Nuclear Spectroscopy there have been significant advances in a number of areas. In collaboration with Professor C-B. Moon the Group has continued studies on soft nuclei with a comprehensive set of measurements on the odd-odd iodine isotopes, ^{118}I, ^{120}I, ^{122}I, and ^{124}I, resulting in extensive new information on the competing effects of shape changes and the coupling of proton and neutron orbitals.

Other studies of odd-odd nuclei have focused on the isotopes of tantalum, in particular ^{180}Ta and ^{176}Ta in a range of light-ion-induced studies intended to complement our extensive studies with heavy ions. Heavy ions favour the population of high-spin states, while fusion reactions induced by light ions, protons and deuterons, offer the hope of exposing the intermediate and low-spin structures. Both low and high-spin structures are needed to characterise such odd-odd nuclei, but an additional interest in ^{180}Ta is our claim that specific low-*K* rotational bands provide the pathway for the destruction of ^{180m}Ta in hot stellar environments, through resonant photon scattering and subsequent decay to the short-lived ground state.

Another major area of interest is shape co-existence, particularly in the region of the very neutron-deficient lead isotopes. Analysis of measurements carried out using Gammasphere at the Lawrence Berkeley National Laboratory and aimed at characterising the isomeric states identified in ^{188}Pb in our earlier work, have been completed and have provided comprehensive information on the subtle effects of triple shape co-existence in that nucleus. These results have also provided the basis for studies of the odd-odd and odd-A Tl isotopes whose spectroscopy should show the effects of uncoupled protons and neutrons on the underlying potential.

Related studies have focused on anomalies in the strengths of E3 branches from the 11^- yrast states. Following resolution of those problems in ^{192}Pb and ^{190}Pb, we have extended the measurements to ^{194}Pb, for which the published data were also anomalous, and finally to ^{196}Pb, where no branches were known. This has provided results from a range of lead isotopes that match neutron-deficient polonium cases and should allow a direct test of our contention that the large E3 strengths all have the same origin, specifically hybridisation of the 8^+ final state induced by oblate deformation.

A more dramatic example of shape co-existence in heavy nuclei is the phenomenon of Superdeformation. Despite the identification of over 150 examples, only a handful have been definitely linked into the spectrum of excited states, leaving their fundamental quantum characteristics uncertain. By bringing together the isomer techniques developed locally with the efficiency of Gammasphere at the Lawrence Berkeley National Laboratory, we have successfully identified direct decays from the Superdeformed band in ^{192}Pb, thus establishing its excitation energy and providing a test of mean-field models. Further experiments in this direction are planned.

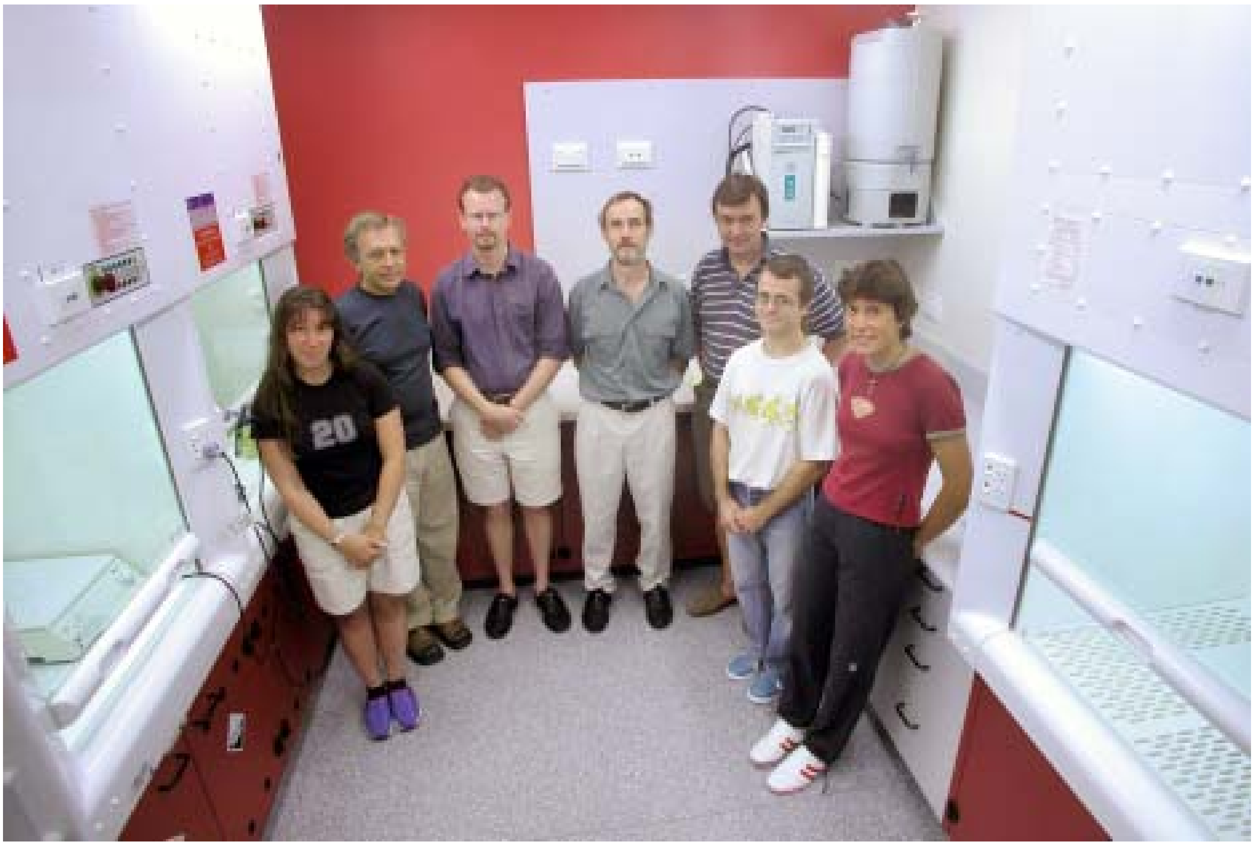
Professor Dracoulis, Dr Lane and Dr Byrne also participated in the first spectroscopy measurement with re-accelerated radioactive ion beams at the new SPIRAL facility at GANIL. The proposal was built on our interest in neutron-rich heavy nuclei such as ^{212}Po and ^{213}At, and aimed to use the (^{8}He,4n) reaction with the EXOGAM array, in its commissioning phase. In conjunction with such measurements we have continued to use the 14UD for incomplete fusion reactions to complement the information emerging from our experiments with deep-inelastic reactions, carried out locally and at Argonne National Laboratory. The main focus of these studies is the identification of configurations which involve the valence particles outside the N=126 and Z=82 cores, part of a collaboration with the Cracow, Berkeley and Argonne groups. A further development has been the instigation of a collaboration with the theory group of Covello (Naples) who are using the shell-model with realistic interactions to calculate the primary valence configurations in this region.

The new perturbed gamma-gamma correlation techniques for measuring excited state moments in radioactive nuclei (Robinson, PhD thesis) have led to elucidation of the role of quasiproton excitations in the high-spin continuum of neutron-deficient platinum nuclei. The formalism developed has also allowed the extraction of the spectroscopic quadrupole moments of the first excited states of the even-even isotopes $^{180-184}$Pt, the first measurements of quadrupole moments on such short-lived excited states in unstable nuclei.

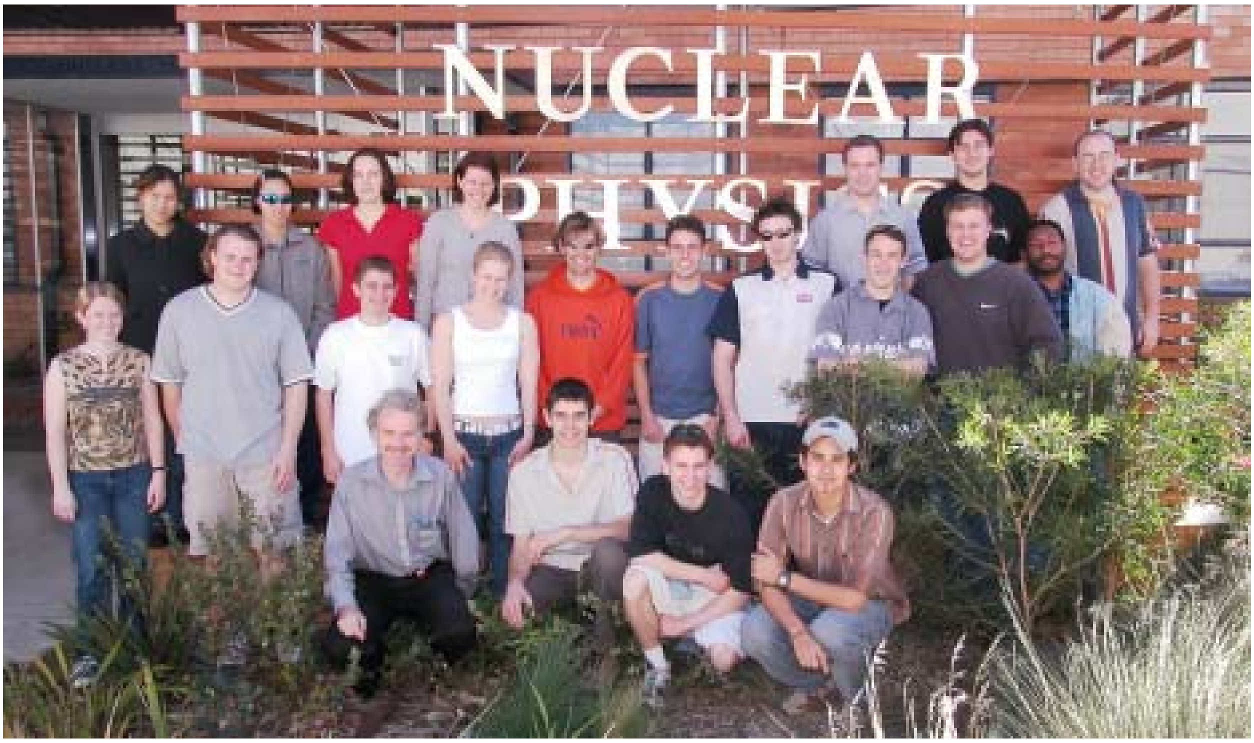
While the studies described above are aimed at an understanding of basic nuclear processes and properties, other research activities have concentrated on the development and application of nuclear techniques to a broad range of scientific activities.

For example the implantation of long-lived nuclear species with known nuclear moments into special materials allows one to probe the properties of the materials by interpreting the perturbations of the nuclear ensemble caused by the local electric and magnetic fields. Such studies of Perturbed Angular Correlations and Hyperfine Interactions in Materials have been applied to semiconductor materials using both ^{111}In and ^{100}Pd radioactive probes. The ^{100}Pd work has focused on gettering by cavities in silicon as part of characterisation that includes EXAS, RBS and XTEM measurements. Distinct differences in PAC spectra have been observed, however it is not yet clear whether these are attributable to the migration of the ^{100}Pd probe into the cavities, or to a modification of the environment within the bulk material. The ^{100}Pd probe has also been used to investigate sapphire material, the initial result being that the anomalous behaviour observed as a function of temperature when ^{111}In was used as the probe, is not present.

To date, these radioisotopes have been introduced into the samples by a direct production/implantation technique using beams from the 14UD accelerator but this year has also seen considerable progress on the development of the ANU/ADFA 150 keV ion implanter located in the School of Physics at the Australian Defence Force Academy, UNSW. Beams of stable indium have been developed and the first implantations of radioactive ions, such as ^{111}In, is expected in 2003. Low energy implantation of radioactive ions will complement the high



The AMS Group, Laura Gladkis, Tez Esat, Tim Barrows, Keith Fifield, Vlad Levchenko, Steve Tims and Susi Olivier (visiting from Berne, Switzerland) in the sparkling new sample preparation laboratories



Students from University of Wollongong and ADFA who participated in the 2002 Workshop on Nuclear Techniques hosted by the Department of Nuclear Physics

energy recoil implantation of probe nuclei and open up new research possibilities in the areas of materials characterisation with Perturbed Angular Correlations (PAC) and Nuclear Magnetic Resonance of Oriented Nuclei (NMRON).

Work has also commenced on the study of amorphisation and annealing effects caused by electronic stopping of very heavy ions with energies around 100 MeV in compound semiconductors

Other activities in the area of materials characterisation with heavy-ion beams include the techniques ofÄHeavy Ion Elastic Recoil Detection Analysis (ERDA). These have concentrated on the stoichiometric analysis of III-V semiconductor films such as GaN, InN and GaAsN, involving researchers from the Department of Electronic Materials Engineering, Macquarie University, and the School of Physics at the Australian Defence Force Academy, UNSW. A particular challenge is nitrogen depletion during analysis, which is most severe for InN. A model has been developed, which describes the depletion as a function of projectile fluence, so that the original nitrogen content of the samples can reliably be extrapolated. The ERDA results have contributed to an improved understanding of film growth conditions and structural and electronic properties of the films.

In related instrumentation development, research into the magnitude and origin of the pulse-height-deficit effect in gas ionisation detectors, as employed for ion beam analysis and accelerator mass spectrometry, continued with experiments probing the dependence of this effect on gas pressure. It was found that for propane gas, even for the heaviest ions the magnitude of the effect changes little over the range of practical gas pressures.

Another major application is Accelerator Mass Spectrometry (AMS) which uses the combination of a high efficiency (small sample) ion source, tandem acceleration, and heavy-ion detection and identification techniques, to make highly-sensitive measurements of low abundance isotopes.

AMS projects in 2002 were spread across a broad spectrum of isotopes, from ^{10}Be to plutonium with new developments in the use of ^{129}I and ^{99}Tc, both of which required substantial refinements to chemical preparation and detection systems. It was also shown that radium isotopes can be measured with a sensitivity comparable with the best available from other techniques, but with considerable reduction in sample preparation and measurement time.

Commissioning of new chemistry and sample preparation laboratories has resulted in the enhancement of the in-house capabilities, allowing routine preparation of ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl and plutonium samples, in addition to the ^{129}I and ^{99}Tc noted above. Techniques for radium are also being refined. In the case of ^{10}Be, rapid progress in achieving consistently good samples of BeO was made possible by the use of ^{7}Be, produced with the 14UD and the (p,n) reaction, to trace beryllium through the various steps of the procedure. Similar reactions have been used to produce ^{95}Tc^{m} and ^{96}Tc for use as chemical-yield tracers during preparation of ^{99}Tc samples.

Considerable effort continues to go into ^{10}Be for a number of projects on landscape denudation and sediment storage, including studies of catchment area evolution (Sierra Nevada Mountains of southern Spain, San Bernadino Mountains of California), landslide dating (Hong Kong) and sediment tracking (Yangtze River system in China and various Australian sites). Collaborations with groups in Glasgow, Edinburgh, Hong Kong and RSES are ongoing and the Department has hosted several overseas students and visitors for these projects.

An attempt is also being made to constrain the dates of the disappearance of glaciers from the Snowy Mountains by ^{14}C dating of scarce charcoal fragments from basal sediments in Blue Lake. In another collaboration with the Department of Geology, a radiocarbon chronology has been established for a marine core from the southern end of the Great Barrier Reef with the aim of interpreting climatic signals in the core, and the evolution of coral reef formation on Heron Island is also being determined via radiocarbon ages of ancient corals retrieved from drill cores.

The focus this year of the groundwater collaboration with the Bureau of Rural Sciences (BRS) was on a joint collaboration with a group in Japan to study possible nuclear waste storage sites.

Technetium-99 is finding application as an oceanographic tracer and as a biological tracer in humans. Controlled releases of this isotope and of ^{129}I from the nuclear reprocessing plants at Sellafield and La Hague are well documented, and hence the ^{99}Tc/^{129}I ratio has considerable potential as an oceanographic tracer in the north Atlantic Ocean, a region which plays a key role in the Earth's climate. In collaboration with a group in Paris, who perform the ^{129}I measurements, ^{99}Tc in samples of seawater from the Norwegian coast have been measured in order to validate earlier β-decay studies on seaweed. In the longer term, the intention is to measure the isotope in deep-water regions where seaweed is not available.

There is also a public health aspect as ^{99}Tc is concentrated along food chains to humans. In order to study potential radiological consequences of human consumption of seafood, we have shown that concentrations of ^{99}Tc in various bodily fluids can be readily determined by AMS, allowing reliable measurements of uptake and excretion. This work is in collaboration with Professor D. Oughton of the Agricultural University of Norway. Also in collaboration with Professor Oughton, plutonium isotopes in water and sediment from the estuaries of rivers in northern Siberia whose catchments are located near Nuclear-weapon production plants of the former Soviet Union have been measured.

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Plasma Research Laboratory

Professor Jeffrey Harris - Head of Plasma Research Laboratory

The Plasma Research Laboratory investigates the physics of plasmas, the fourth state of matter, a subject of fundamental significance as well as of immense practical benefit to humankind.

http://wwwrsphysse.anu.edu.au/prl

Ionised gases—plasmas—make up 99% of the visible universe, and plasma phenomena are important in everything from stars and space exploration to the processing of electronic materials. Plasma physics is thus a highly interdisciplinary endeavour because of the range of physics areas it encompasses (fluid, atomic, electromagnetic, optical and surface physics) and the diverse technologies employed in plasma experiments (electronics, radio-frequency technologies, magnetics, lasers and microwaves, and spectroscopy).

Experimental plasma research in the Plasma Research Laboratory (PRL) centres on two types of systems:

The H-1 National Facility Heliac operated by the Laboratory's Toroidal Plasma Group is a large toroidal helical-axis stellarator device that is used to carry out fundamental research in the physics of plasma confinement for the production of electricity using fusion reactions like those that power the Sun. The heliac magnetic field is produced by a precision three-dimensional magnetic system. The plasma is produced by high-power radio and micro-waves, and its properties are measured by electric and magnetic probes, optical and microwave interferometry and scattering instruments. A particular focus of work on the heliac is the study of turbulent transport, flows, instabilities and magnetic configurations on plasma confinement. Technologies originated in research on the heliac are also being applied to plasma diagnostics for experiments around the world, instruments for industry and defence, and wireless communication and radar.

Helicon Plasma Sources, high-density linear magnetic plasma devices driven by radio-frequency waves, were originated by the Laboratory's Space Plasma and Plasma Processing Group, and now come in many configurations, from the large WOMBAT experiment to small systems that can be transported in a suitcase. They continue to serve as a focus for basic research in wave-plasma interactions, flows, and potential structure, as well as a basis for innovative devices for technological application. Current activities include the use of helicon plasma processing systems for the processing of electro-optic materials, the development of high-brightness ion sources, and the development of compact plasma thrusters for deep space travel.

The Laboratory also performs research in plasma theory, simulation, and visualisation, in collaboration with staff from the Department of Theoretical Physics and the Department of Computer Sciences in the Faculty of Engineering and Information Technology.

PRL staff are deeply involved in educating young scientists and engineers, through the supervision of post-graduate thesis research and fourth-year undergraduate research projects. We also regularly host students from around the world who come to take advantage of the Laboratory's special capabilities. Staff members of the Laboratory also contribute to undergraduate lecture and laboratory courses offered by the Department of Physics and the Department of Engineering in the ANU Faculties.

The Laboratory maintains extensive international research connections via collaborative research projects as well as externally sponsored research contracts. In 2002, the Laboratory hosted the 14th International Stellarator Workshop and co-hosted the 2002 Gaseous Electronics Meeting (GEM) and the 2002 International Conference on Plasma Physics (ICPP).

Toroidal Plasma Confinement

The centrepiece of toroidal confinement research in PRL is the H-1 Heliac Plasma National Research Facility. This facility is a three-field period helical axis stellarator, which has a major radius of 1 metre, mean minor radius of about 0.2 m and is characterised by a wide range of magnetic configurations. A variety of plasma conditions are accessible, from weakly magnetised argon plasma at 0.1 Tesla, to highly magnetised hydrogen plasma up to 1 Tesla, with temperatures in the range of tens of thousands to millions of degrees. Highlights of developments of the plasma generation and electron and ion heating systems, and the results of physics studies are highlighted below.

Development of the H-1 National Facility

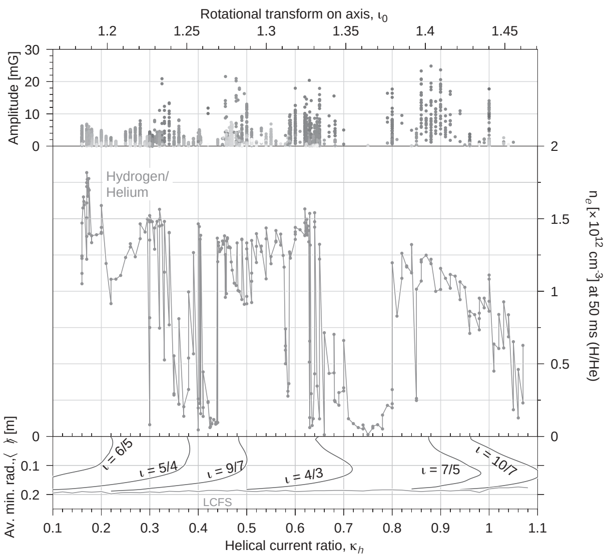
In 2002, two new facility milestones were met, and a record number of shots were fired, in between moving all the H-1 support laboratories and workshops and hosting/supporting two international conferences.

The electron cyclotron resonance heating (ECRH) system delivered more than 150 kW at 28 GHz into H-1 in April, producing the highest plasma energy to-date. Confirmation of temperatures awaits further data. The ECRH power supply capability has been extended from 10ms to 40 ms.

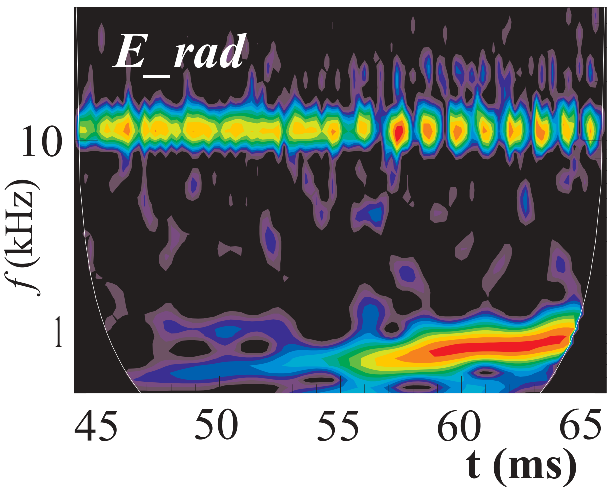
Another newly commissioned system has delivered 200 kW of radiofrequency (RF) power into H-1, achieving another milestone. Power at 0.5 Tesla to heat hydrogen plasma was increased to >120 kW. This complements the 7 MHz RF system used to create plasma and heat both ions and electrons.

Impurity studies show that for our cleanest plasma conditions, light impurities (carbon and oxygen) are dominant. These conditions are achieved with ECR heating, or RF heating near a low order resonance in rotational transform. A low temperature vacuum baking system (maximum of 90°C) has been commissioned, and initial tests successfully demonstrated a marked acceleration of outgassing of H_2O, a major impurity. Gas control has been improved by installation of a five-way flow control system and a second puff valve.

Around 4600 plasma shots have been performed in 2002 of which half were in high field (0.5 Tesla) hydrogen/helium plasma. In order to diagnose higher temperature plasma, new remote diagnostics are being commissioned, such as correlation spectroscopy for fluctuation studies and a second multi-channel Doppler spectroscopy system (MOSS). New automated scanning software allows data to be taken more efficiently and reliably, and a new Rogowski loop and 20-coil external magnetic probe (Mirnov) array provides measurements of plasma current and fluctuations. To simplify H-1 operation, installation of two additional PLC control systems has commenced.



Dependence of density and magnetic fluctuations on rotational transform in the H-1NF heliac



The Figure shows the development of a zonal flow: low frequency (<1 kHz) spectral feature develops as a result of the non-linear interactions of the higher frequency fluctuations. Once developed, it starts modulating parent waves.

Data Acquisition and Data Mining

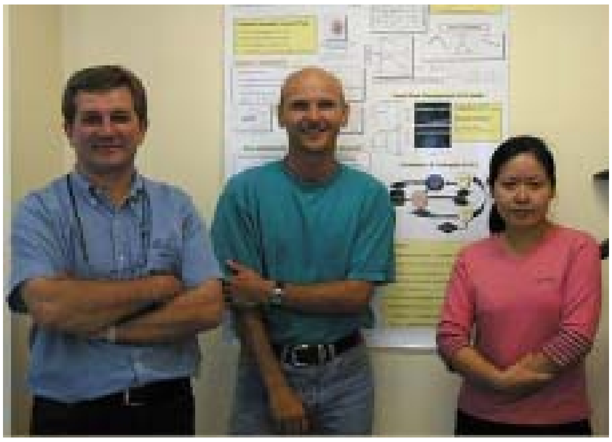
More than 50,000 plasma pulses have been recorded in total under "MDSPlus", and are being distilled into a "summary" database and an "electronic log book", small enough to fit on a business card. In 2002, these were integrated through a Web interface, and work commenced on data mining techniques to best exploit the data. Machine learning techniques showed promise in evaluating the quality of data, and association techniques were applied to explore signatures of magnetic fluctuations in hydrogen/helium plasma at higher fields.

Magnetic Configuration Studies

The main feature of the "flexible heliac" is the ability to change the shape of the magnetic confinement region (configuration) in several dimensions, such as shape, rotational transform ("twist per turn"), and the depth of the minimum in magnetic field ("magnetic well", related to stability). Studies of the confinement of hydrogen/helium plasmas heated with ion-cyclotron waves using very fine scale (steps <0.5%) scans of the rotational transform show that the density confined in the heliac is very sensitive to the presence of surfaces with rational values of the rotational transform inside the plasma volume. When the rotational transform profile crosses multiple low order rational (e.g., 4/3) surfaces, the density drops to very low values, as is illustrated in the figure on the left. Fluctuations in the magnetic field also show a fine structure that changes with rotational transform.

Plasma Turbulence and Transport Physics

The physics of plasma turbulence covers a broad spectrum of fundamental physics problems, such as turbulence development, self-organisation and self-regulation, as well as problems of the particle and energy loss in the toroidal plasmas crucially important for fusion research. The Group continues broad experimental studies into turbulence and transport contributing to both basic plasma physics and to fusion research.



Dr M. Shats, H. Punzmann and H. Xai with the poster summarising turbulence and transport highlights of the year

We reported the first observation of zonal flows in plasma in Shats M.G. and Solomon W.M. *Phys Rev. Lett.* 88, 045001 (2002). Plasma zonal flows were theoretically predicted in 1979, found in computer simulations in 1998 and were observed in the H-1 heliac in 2001. Zonal flows are large-scale anisotropic structures, which are generated in the plasma by the turbulence via three-wave interactions. They affect their parent waves leading to the self-regulation of the plasma turbulence. Detailed studies of the effects of zonal flows on other turbulent structures and their role in saturating the turbulence levels have commenced. The analogy between plasma zonal flows and their relatives in planetary atmospheres will be further investigated.

Electric Fields in the Plasma and their Effect on Turbulence and Transport

Electric fields play a major role in plasma transport. They interact with plasma turbulence, can destroy turbulent vortices and accumulate fluctuation energy thus improving plasma confinement. Their generation and a complex interplay with the turbulence is a subject of the on-going collaboration with the University of California at San Diego.

Turbulent Structures and Plasma Self-Organisation

Plasma turbulence in toroidal configurations can self-organise into large turbulent structures or vortices. The presence of large vortices in the plasma leads to enhanced convective losses of particles across the confining magnetic field and deteriorates plasma confinement. When these structures are suppressed by shear flows, transport properties of the plasma are improved. Visualisation of turbulent vortices using novel diagnostics and signal analysis tools as well as studies into the mechanisms of the vortex generation are the main thrusts in this experimental area.

Plasma Diagnostics for Turbulence and Transport Studies

A number of diagnostics for studying the plasma turbulence has been developed and installed on the H-1NF. These include a four-channel heterodyne microwave (2 mm) scattering system, a 20-channel cross-correlation spectroscopy diagnostic combined with the 10-channel spectroscopy for particle transport analysis, and also Langmuir, Mach and magnetic probe arrays.

Development and Application of Advanced Signal Analysis Techniques

Modern methods of analysis of turbulent signals are powerful tools, which go beyond traditional linear, time-averaged spectral turbulence characterisation. Examples include time-resolved spectra using wavelets, higher order spectral analysis (bispectra, trispectra), statistical characterisation of turbulence, conditional analysis, etc.

Advanced Plasma Diagnostics

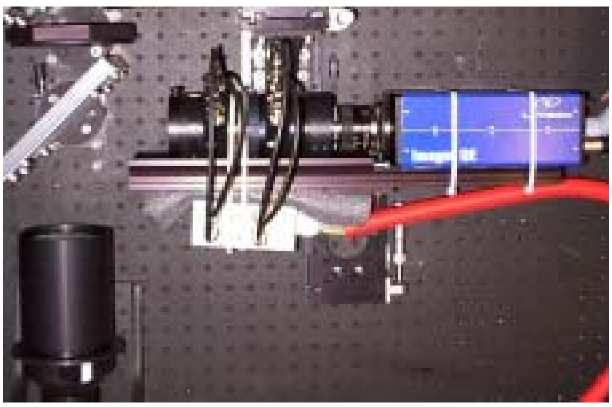
Remote Sensing and Inverse Methods

Understanding the physics of high temperature plasma confinement relies crucially on non-perturbing remote sensing tools. In recent years PRL has pioneered a number of radically new optical measurement systems that are now also being adopted at some of the world's premier fusion laboratories. Related systems are also finding application in industrial process control. To fully utilise the new measurement capabilities, the Group continues to develop the inverse mathematical methods that allow the unfolding and interpretation of the projection data.

A number of advanced imaging measurement systems based on the recently patented MOSS spectrometer (US patent #6462826, 2002) are now installed and operating routinely on H-1. The MOSS spectrometer is a modulated fixed-delay Fourier transform spectrometer based on solid electro-optic birefringent components. It is used for a wide variety of spectroscopic studies (e.g. polarisation and Doppler spectroscopy) of transition radiation from neutral atoms and ions. Growing interest from overseas groups led to the presentation of an invited talk at the German-Polish EURO Conference on Plasma Diagnostics for Fusion and Applications and to the sale of a custom imaging system to the Max Planck Institute for Plasma Physics in Germany. Another system is being developed for ion temperature measurements on the high-field tokamak Alcator C-MOD at MIT.

Ion Heating and Fuelling in H-1

The MOSS systems have been used for the study of plasma heating and force balance in low-field (0.1 T), low-temperature argon discharges. The discovery of a significant non-thermal contribution to the ion velocity distribution function, and its



The MOSS camera installed on the Wendelstein 7-AS stellarator in the Max Planck Institute for Plasma Physics in Germany localisation primarily to the plasma edge regions, suggests that ions are directly heated in H-1 through stochastic interaction with the radio-frequency sheath attached to the heating antenna. Time resolved behaviour of hydrogen and deuterium atom relative densities obtained by MOSS imaging spectroscopy have revealed the liberation of hydrogen from plasma-facing wall components as a major particle source.

Interferometry

The far-infrared (FIR) rapid-scan interferometer continues to operate reliably and has provided routine electron density profile information for a number of studies. It will be used together with the MOSS spectrometer and a calibrated directional gas injection system for particle control (under development).

Thermal Imaging

High-throughput, visible-near-infrared interferometric sensors for remote temperature measurement have been developed in 2002. Related to the MOSS spectrometer, the new filters are an attractive alternative to traditional radiometric systems and are also the subject of provisional patent protection. An ACT Knowledge Fund grant ($40,000) has been awarded for the development of an absolute spectro-radiometer based on these new devices for molten steel imaging at BHP-Billiton in Wollongong. The Remote-Sensing Group has also largely completed a contract ($99,000) with DSTO for the development of sensors for the infrared discrimination of rocket and engine infrared signatures.

Doppler Tomography and Inverse Techniques

We have established the conditions under which the inhomogeneous velocity distribution function can be retrieved from Doppler tomographic measurements. Inverse algorithms, which confirm these findings, have been developed. New Abel inversion methods based on general splines with non-linear optimisation of knot locations have been developed and used for inversion of the brightness, temperature and flow field projections obtained from the interferometer and MOSS systems. We are also collaborating with Chalmers University in Sweden on microwave probing systems and associated finite-difference time-domain inverse techniques for detection and localisation of human breast lesions.

Laser Induced Fluorescence

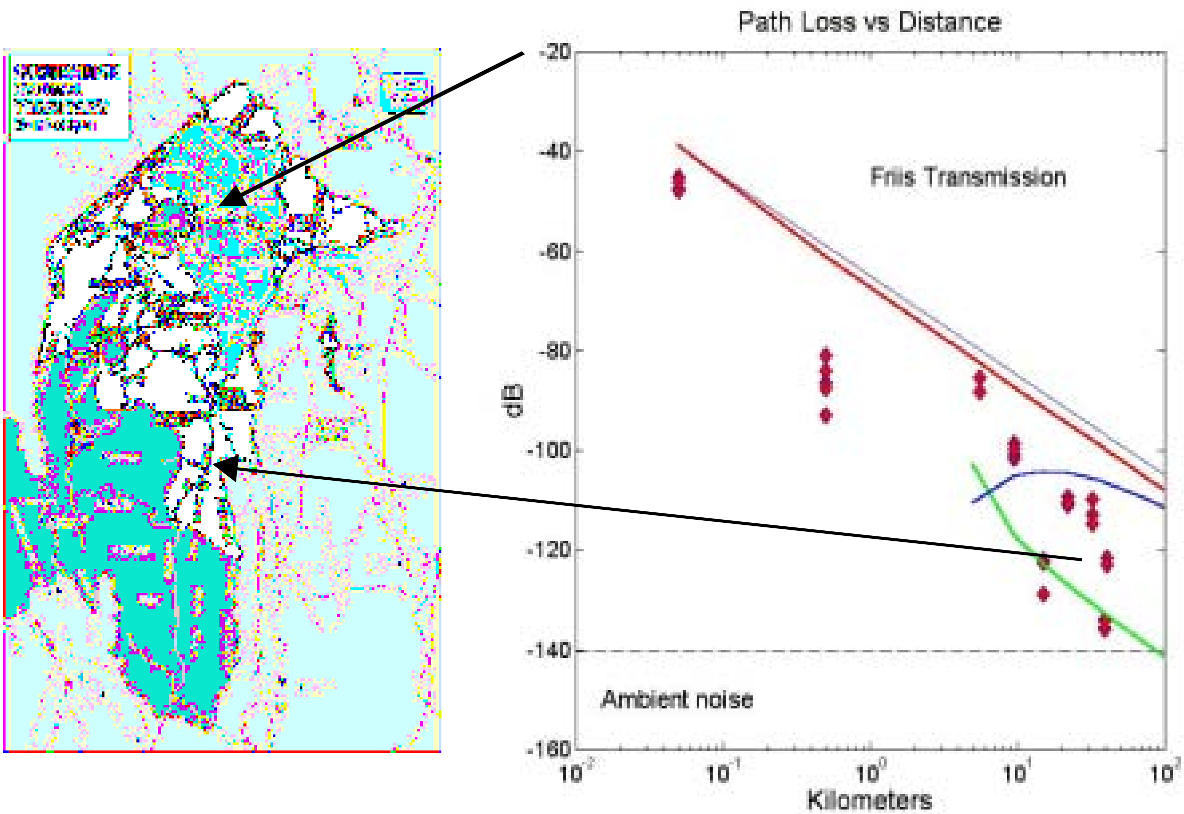
This collaborative project with the University of Sydney received ARC funding for three years commencing in 2000. The aim of the project is to develop techniques for measuring electric fields in plasmas using the laser excitation and fluorescence of metastable helium atoms in a pulsed helium beam.

Wireless Communications

The BushLAN Project

The BushLAN (Bush Local Area Network) project aims to develop technology to support moderate speed (100–200 kbps) VHF wireless data links over non-line of sight distances of 5–100 km to improve Internet connectivity in sparsely populated regions like regional Australia. These links would use vacant VHF TV channels. This technology is being explored by PRL and several industry groups, and was singled out for mention in the 2002 Australian Parliamentary Inquiry on Wireless Broadband Technology.

Earlier this year the BushLAN Group performed channel sounding experiments in the Australian Capital Territory using channels



Results of VHF channel test in the Australian Capital Territory

0 and 1 at frequencies around 50 MHz. The tests indicate that VHF wireless data transmission is feasible over significant distances at very low powers (40 km at 20 W). The figure below shows the path loss as a function of distance in the ACT. The transmitting antenna was located atop Mount Ainslie and the received signal was measured in various places as far south as Naas (40 kms). The straight line is the theoretically predicted path loss for line-of-sight. Hilly terrain would have blocked the signal were operation at microwave frequencies. These results indicate that transmission at > 250 kbps with a bandwidth of 250 kHz is possible, and have led to the development of a design for a low-cost digital transceiver unit for field network trials that is being prototyped in RSPhysSE with the support of a grant from the ACT Knowledge Fund.

In 2002, five students completed honours projects connected with BushLAN. Four more honours students and four post-graduate students are now starting more advanced BushLAN projects that include transceiver and software development, channel studies, and field trials of prototype systems with Etherwave Networks in Wollongong.

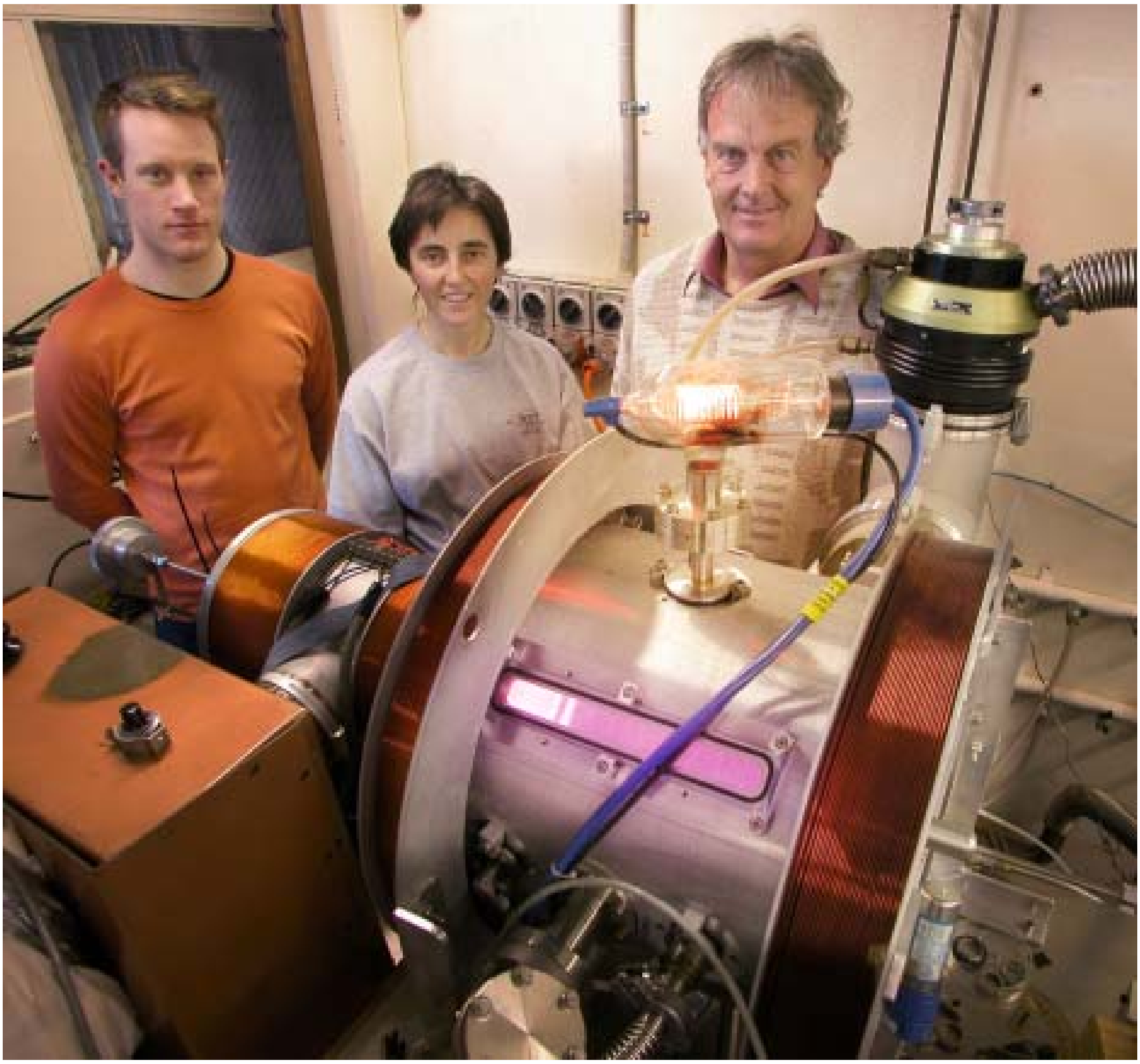
Plasma Lenses and Antennas

In other wireless work, Peter Linardakis is developing plasma RF switch concepts for mobile telecommunications in a PhD project sponsored by Motorola-USA. In 2002, he completed an exchange visit to the Motorola research laboratory in Illinois.

Dr Lise Caillault of the Office National d'Etudes et de Recherches Aerospatiales (France) is doing a post-doctoral project in the Laboratory on the use of plasmas to form microwave dielectric lenses in collaboration with the Australian Defence Science and Technology Organisation. She is looking at the effects of phase noise from the lens on radar applications.

Space Plasma and Plasma Processing

The Space Plasma (SP^3) group is primarily concerned with the basic physics of gaseous discharges and their application to a variety of industrial processes. The Group, shown below, is internationally recognised as leading the way in many developments, in particular, the plasma modification of surfaces, the development of high density plasma sources and the use of expanding plasmas for spacecraft thrusters.



Orson Suthereland, Dr Christine Charles and Professor Rod Boswell with the prototype plasma thruster

Dr Boyd Blackwell shows visitors the H1-NF during the "Machines that Ate Acton" tours

Plasma Thruster

A totally new phenomenon has been experimentally discovered in the SP^3 Laboratory, an electric double layer in an expanding plasma. This was found at low pressures where the simple Boltzmann expansion of a plasma breaks down and the plasma flow becomes supersonic. Although experiments are continuing, a patent has been applied for in the application of this effect to plasma thrusters for space craft and also to the alteration of surfaces. With this new research thrust, we are developing collaborations with NASA in Houston and a number of French groups.

Ion Beam Extraction

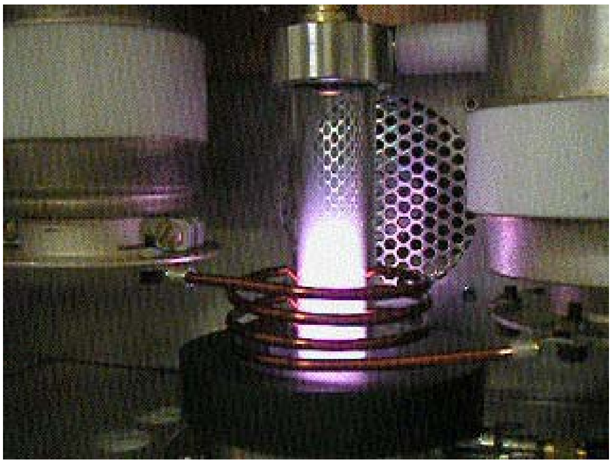
This year has seen the development of several new features in the ANU ion source project. Two significant collaborations have been undertaken. The laboratory hosted Dr M. Irzyk from France and Dr J. Keller from the USA. They have complimented the experimental work of plasma density and beam shape measurements with computer simulation studies. Major milestones have been achieved this year including significant gains in plasma density by increasing power, reducing source size, and optimising the magnetic field.

Cross-Field Diffusion in Helicon Plasmas

Helicon plasmas are known for their high density and high ionising efficiency. Much has been published on the possible wave mechanisms for accelerating the plasma electrons but virtually no concerted study has been made on the details of the plasma confinement. Recent experiments in the SP^3 Laboratory have shown that there appears to be a form of radial electrostatic confinement associated with the high density 'blue core' plasma.

Ion Heating in the Plasma Presheath

It is known that ion interaction with neutrals in the presheath of a plasma can define the actual length of the presheath.



Ion Beam Plasma Source

However, there have been few detailed experiments done on measuring the energy input to the perpendicular and parallel ion temperatures. We are collaborating with a group at UC Irvine on Laser Induced Fluorescence and Dr Helen Smith who uses particle-in-cell simulations to determine the evolution of these ion temperatures. The perpendicular temperature in particular is of crucial importance in defining the brightness of focussed ion beams.

Effect of Antenna Immersed in Laboratory Plasmas, e.g., H1 Heliac, Helicon

A plasma source excited by a double saddle helicon antenna has been modified by inserting a second electrically floating copper antenna in contact with the plasma through the glass end plate. For low helicon powers, the density decreases with time but for high powers, a copper free path is left in the glass adjacent to the helicon antenna due to re-sputtering of the deposited copper and no change in the plasma density is observed.

Particle-In-Cell Simulation of RF Breakdown in Plasmas

Experimental measurements and particle-in-cell simulations are used to investigate breakdown in radiofrequency plasmas. The RF "Paschen" curve requires significantly lower voltages and only the left hand side of the curve is affected by the secondary emission characteristic of the electrodes.

Helicon Source Modelling

A model of the energy balance based on the experimental data has been developed by initially modelling the plasma sheath along the double-saddle antenna of rather complex geometry. For the present capacitive coupling, the RF antenna voltage is mostly dropped across the sheath and the glass surface along the antenna charges negatively like the bias capacitor in an asymmetric discharge. Consequently, the main power deposition terms correspond to ion acceleration into the glass along the antenna and to the subsequent ion-induced secondary electrons, both contributing to the low power transfer efficiency of this capacitively coupled discharge.

Planar Optical Waveguides

The HARE Group has been working on the plasma deposition of germanium doped silicon dioxide for the fabrication of hydrogen-free planar optical waveguides with low loss in the 1200–1600 nm range. Photolithographic processes and HF etching were developed for waveguide fabrication and optical tests on thick deposited films. The preliminary results of the rib

Scott Collis of PRL demonstrates plasma phenomena to school students during the Australian Science Festival waveguides fabricated show low propagation loss (<1 dB/cm) at red light. To improve the rib waveguide fabrication morphology on the deposited films a plasma etching process has been developed. A Fourier Transform IR spectroscopy study combined with an experimental study of the stress lead to some insight into the bulk properties of the plasma deposited films.

Wall Charging in Helicon Plasmas

Wall charging is a contributing factor to plasma process drift in production lines especially when insulating materials are being deposited or etched. For our silicon dioxide plasma deposition process, the magnitude of the wall charging most likely depends on the effective capacitance formed by the silica layer and on the imbalance between the positively and negatively charged particles which impinge onto the sidewalls at the discharge initiation until equilibrium of fluxes is reached.

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Professor Yuri Kivshar
- Head of Nonlinear Physics Group

Professor John Love
- Head of Applied Photonics Group

The Theory Cluster comprises the Department of Theoretical Physics, the Nonlinear Physics Group, the Applied Photonics Group and the Optical Science Centre. Each group has its own head of department and each group is independently administered.

Department of Theoretical Physics

Research Summary

The study of physics involves the discovery of quantitative laws of nature. The challenge for theoretical physics is to unravel these laws and to elucidate their consequences. The research in the Department covers a broad spectrum of activities including atomic and molecular physics, biophysics, condensed matter physics, nuclear physics, plasma physics and statistical mechanics and field theory.

The Department continued its success in the ARC Discovery program. In addition to the large grants in the area of statistical mechanics and field theory awarded for 2002–2004 to Professors Bazhanov and Baxter, Professor Batchelor was awarded \$1.1 million for 2003–2007, including an Australian Professorial Fellowship. In biophysics, Dr Chung was awarded \$1 million for 2002–2004 for research on biological ion channels. Other new grants for 2003–2005 include \$600,000 to Dr Ball, Professor Dewar and Dr J. Frederiksen (CSIRO) in plasma physics and \$300,000 to Dr Kheifets, jointly with Dr Vos and Professor Weigold (AMPL), in electron momentum spectroscopy.

The Department is host to the Centre for Complex Systems (CCS). The Centre's activities are highlighted elsewhere.

Atomic and Molecular Physics

Ultrafast Coherent Dynamics of Localised Modes in Many-Body Systems

The use of femtosecond laser pulses is a celebrated tool for the real-time monitoring of ultrafast coherent molecular dynamics, important, e.g., for environmental science and biology. This method is restricted to unimolecular reactions only. It was shown that the bimolecular collision experiments with pure energy resolution can provide information on the reaction dynamics equivalent to that obtained using standard femtochemistry methods. This allows the study of ultrafast coherent dynamics of localised modes, e.g., in heavy-ion collisions, electron-molecular scattering, atomic cluster collisions and electron scattering from nanostructures. It was demonstrated that in some instances the method provides time resolution of six orders of magnitude better than conventional methods of femtochemistry. Some projects have been carried out in collaboration with AMPL.

Many-Body Localised Modes and Nonergodic Molecules in Continuum

Very strong sensitivity of the cross section energy autocorrelation functions to the relaxation time of localised modes excited in microscopic and mesoscopic collisions has been demonstrated. The extremely stable many-body localised modes in nuclear molecules confirm an earlier prediction that the dephasing can be much slower than the intramolecular energy redistribution, with these modes surviving a thermalisation of the highly excited many-body system. The localised modes result from coherent superpositions of a very large number of strongly overlapping many-body molecular resonances producing unusual states — nonergodic molecules in continuum. Anomalously long dephasing times observed in highly excited polyatomic molecules may reflect this new type of nonergodicity.

Biophysics

There is a great deal of diversity among the potassium channels observed in nature. Their conductance levels vary by almost two orders of magnitude yet they all exhibit the same selectivity against sodium ions. The latter property is explained by the fact that the structure of the selectivity filter found in the KcsA potassium channel is conserved among all the potassium channels. But the observed KcsA structure sheds little light on the diversity problem. To investigate this problem, a model was constructed with potassium channels having similar structures to KcsA but differing in their intra-pore radius. Electrostatic calculations of the multi-ion potential energy profiles revealed that the central energy barrier decreases with increasing intra-pore radius. This leads to an exponential increase in channel currents as confirmed by Brownian dynamics (BD) simulations. Thus the large variations in conductance of potassium channels are understood in terms of structural changes in the intracellular side of the protein that is known to differ widely among the potassium channels.

Work on gramicidin channel continued with the emphasis shifted from continuum electrostatics, which was shown to break down previously, to deriving the potential of mean force (PMF) of ions in the channel using molecular dynamics simulations. The PMF profiles obtained using the two popular force fields (GROMACS and CHARMM) yielded large central barriers exceeding 20 kT. This translates to a drastic suppression of channel current incompatible with the experimental observations. The most likely reason for the failure of these force fields is the neglect of the induced polarisation interaction. Work is in progress to include the polarisation effects explicitly in the PMF calculations. A positive result will have far reaching implications for applications of MD simulations to ion channels and other biological systems.

Condensed Matter Physics

Density Functional Theory of Super-Phenomena

Density functional theory is considered as a standard method for studying low energy physics, delivering very impressive results in the study of the normal state of matter. However, experience shows that at low enough temperature the lowest energy state of a many-body quantum system is not really a normal state. Inter-particle correlations in conjunction with statistics connive to form condensates, which exhibit super-phenomena (superconductivity and superfluidity). The occurrence of Fermi and Bose condensates is being studied in the realm of density functionals as fundamental processes. The aim is to obtain a pairing potential that sustains an order parameter due to broken symmetry. At the Hartree mean-field level this theory has produced the well known BCS results. An examination of the adiabatic connection formula is underway.

Mesoscopic Systems and Organic Superconductors

Charge conduction and current noise are intertwined phenomena. A unified description of both quantised conductance and nonequilibrium thermal noise in a one-dimensional ballistic wire, open to macroscopic leads, has been given. While four-terminal measurements in such a conductor give evidence of resistance-free charge transport, its two-terminal resistance exhibits finite universally scaled quantised steps. At the two-probe conductance steps, the excess noise of field-excited ballistic carriers displays sharp peaks much larger than for shot noise. The thermal noise peaks are dramatically sensitive to the inelastic scattering effects in the leads that degrade universal conductance scaling. Thus, high current thermal noise yields unique clues to the origin of contact resistance and the crossover to diffusive conduction.

Transport of charge carriers can be controlled by doping through chemical and physical means. Unlike chemical doping, physical doping is carried out by a special technique through gate voltages in field effect transistor geometry. This technique keeps the carrier channels free from defects without complications from the crystalline structure and the doping density. The occurrence of superconductivity on the interface of a device by an unconventional technique has been studied and a dynamical pairing mechanism governed by the excitons in the active device examined. The pairing of charge carriers takes place when the system is in a nonequilibrium (driven) state. The physics of a plausible superconducting transition has been discussed and new experiments suggested.

Interaction between Semiconductor Nanostructures and Intense Terahertz Laser Fields

The effects of intense terahertz laser radiation on transport and optical properties of semiconductor nanostructures in the presence of quantising magnetic fields have been studied in conjunction with experimental measurements. A theoretical approach has been developed to calculate magneto-transport and magneto-optical coefficients of low-dimensional electron gas systems when a linearly polarised intense laser field (provided by FELIX free-electron laser in Europe) is present.

The effects of intense terahertz laser radiation on hydrogen-like impurities in semiconductor systems have also been studied. A theoretical model has been developed to calculate laser-dressed binding energies and transition energies, with the results obtained from this study to provide a theoretical background for further experimental investigations.

Strong Electronic Correlations and High-Tc Superconductivity

The comprehensive investigation continues into the properties of magnetically ordered phases which appear in one- and two-dimensional strongly correlated systems, using the non-Abelian density matrix renormalisation group developed last year. In one dimension, the properties of the ferromagnetic phases were analysed in the Kondo lattice and periodic Anderson models. In two dimensions, the stripe phase was studied in the t-J and periodic Anderson models. In low-dimensional strongly correlated electron systems the interplay of localised moments and conduction electrons was addressed using Abelian bosonisation. The double-exchange ferromagnetic interaction was studied in the periodic Anderson model. The impact of phonons on the magnetic properties of the Kondo lattice model were analysed and the phase diagram of the model determined. The effect of the localised spin dilution was also studied in the Kondo lattice model. In this case, it was discovered that dilution drives the system to antiferromagnetism.

The nature of high-temperature superconductivity remains elusive despite the many novel models that have been proposed. This problem was studied using a technique based on an infinite order unitary transformation. The transformation was successfully applied to the two and three band, two-dimensional Hubbard models containing phonons. The effective spin and charge interactions were exactly determined.

Nuclear Theory

Quantum Mechanics

It was shown that the momentum density conjugate to a bosonic quantum field splits naturally into the sum of a classical component and a non-classical component with the field and the non-classical component of the momentum density satisfying an exact uncertainty relation. This motivates a new approach to bosonic quantum fields. In particular, the postulate that an ensemble of classical fields is subject to non-classical momentum fluctuations, of a strength determined by the field uncertainty, leads from the classical to the quantum field equations. Examples include scalar, electromagnetic and gravitational fields.

Light Nuclei

Values of the electron-screening potential for various reactions between light nuclei have been obtained from fits to low-energy cross-section data. Measurements of the $^{14}N(^{3}He, ^{6}He)^{11}N$ cross section have been analysed by R-matrix formulae in terms of the six lowest levels of ^{11}N. The two-proton decay widths of the ground and first excited states of ^{6}Be and of the ground state of ^{8}C have been calculated using R-matrix formulae, and are in reasonable agreement with the experiment. The half-life of ^{45}Fe calculated using an R-matrix formula for the contribution due to diproton decay agrees with experimental values provided the available decay is near the upper limit of the experimental range. In contrast with a recent publication, the energies of the lowest $1/2^{+}$, T = 3/2 levels of ^{11}B and ^{11}C from potential-model and R-matrix calculations are found to be found in reasonable agreement with agreement, although there may be disagreements for the widths of these levels.

Antiproton-Deuteron Scattering

Work on fitting the experimental differential cross section for pd elastic scattering at 179.3 MeV employing the pp scattering amplitude obtained from pp scattering experiments to determine the parameters of the elementary pn scattering amplitude at 179.3 MeV has continued. The results are being compared with other analyses.

Generation Model of the Fundamental Particles

A new classification of the fundamental particles (six leptons, six quarks and their twelve antiparticles) and the twelve fundamental 'force' particles (photon, three massive weak force bosons and eight gluons) based upon the use of only three additive quantum numbers (charge, particle number, generation quantum number) compared with the nine additive quantum numbers of the Standard Model (charge, electron lepton number, muon lepton number, tau lepton number, baryon number, strangeness, charm, bottomness, topness) has been developed.

Unlike some of the additive quantum numbers of the Standard Model, the three additive quantum numbers of the new Generation Model are strictly conserved in strong, electromagnetic and weak interactions.

The Generation Model provides a new basis for the weak isospin symmetry characteristic of both leptons and quarks.

Plasma Physics

The structural properties of an economical model for a confined plasma turbulence governor were investigated through bifurcation and stability analysis.

A close relationship was demonstrated between the underlying bifurcation framework of the model and typical behaviour associated with low- to high-confinement transitions such as shear flow stabilisation of turbulence and oscillatory collective action.

In particular, the analysis evinced two types of discontinuous transition that are qualitatively distinct.

One involves classical hysteresis, governed by viscous dissipation.

The other is intrinsically oscillatory and non-hysteretic, and thus provides a model for the so-called dithering transitions that are frequently observed.

This metamorphosis, or transformation, of the system dynamics is an important late side-effect of symmetry-breaking, which manifests as an unusual non-symmetric transcritical bifurcation induced by a significant shear flow drive.

Fusion Theory

A model for transition to shear modes triggered in tokamaks has been proposed. This model takes into account the linear and quasilinear behaviour of the ion temperature gradient driven perturbation, considered nowadays as the dominant source of anomalous energy losses in the low confinement mode. Analytic and numerical studies showed that the sign of the second derivative of the parallel velocity with respect to the radial coordinate determines the mode selection and stability. Theoretical studies were also undertaken to explain the salient features of the RI-mode on TEXTOR-94. Among the results obtained, it was shown that the linear increase in the energy confinement time with electron density can be explained by turbulence originating from the electron temperature gradient driven modes.

Space Plasma

A fundamental reality throughout the space plasmas is the existence of magnetic field-aligned flows. It is usually believed that the spatial transverse shear in the parallel flow destabilises many low frequency instabilities and this may be the origin of low frequency oscillations in the ionosphere. It was shown that this notion of destabilising influence of the shear in the parallel flow can be changed altogether if one takes the effect of the flow curvature (second spatial derivative) into account. The transverse curvature in the parallel flow can overcome the destabilising influence of the shear and can render the low frequency modes stable. This theoretical finding seems to have been supported in the high temperature laboratory plasma experiments at STOR-M tokamak in Canada.

H-1 Theory

Recently there has been considerable interest in whether radio frequency (rf) waves can be used to create the transport barrier to reduce the loss of particles and energy from plasma. The formation of transport barriers by the rf waves, in usual wisdom, relies on the hypothesis of the generation of rf-driven flow shear and consequent suppression of turbulence. Although rf can introduce toroidal flow, the momentum transferred to the electrons from the rf field is dissipated quickly by the background ions and in reality toroidal rotation induced by rf is small. Similarly, poloidal flows have been observed in the last run of experiments in the Tokamak Fusion Test Reactor, but not of the magnitude believed to be required to obtain a barrier. An alternative way of forming transport barrier by rf waves is suggested, with the ponderomotive force induced by rf waves in the range of the Alfven frequency creating a transport barrier in a fusion device. It is shown that if the radial profile of the rf field energy is properly chosen the linear mode is stabilised and turbulent momentum transport reduces. The rf power required for this stabilisation is found to be rather modest and hence should be easily obtained in actual experiments. The relevance of this theory to the experimental data on H-1 will be investigated.

Magnetohydrodynamic (MHD) Spectral Studies

Plasmas support an enormous variety of collective motions and the study of the spectrum of the eigenmodes of oscillation is an important approach to the understanding of plasma behaviour. However, the lack of a continuous symmetry in stellarator magnetic confinement devices, such as the ANU heliac, H-1NF, makes this a challenging problem because the toroidal mode number is no longer a good quantum number and the spectrum may be "quantum chaotic". A data set of approximately 100 negative real eigenvalues of the square of the frequency in a variant configuration of the German W7X stellarator (under construction) has been computed using the ideal-MHD CAS3D code. Two statistical measures have been used for characterising the spectrum — the probability distribution for the separation of eigenvalues, and the Dyson-Mehta rigidity. Both show strong departure from the Poissonian behaviour characteristic of regular spectra in quantum systems, which may be evidence for quantum chaos.

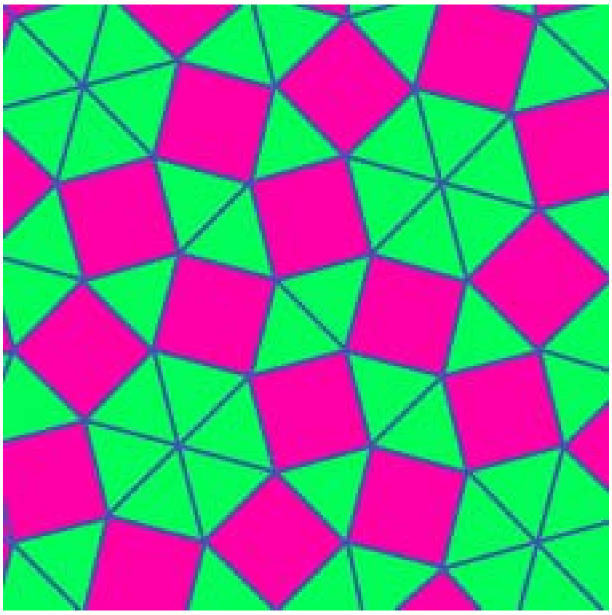
Further work on validating the incompressible resistive MHD code SPECTOR-3D has been performed, and a new compressible version has been written. Analytic studies of the spectrum in a cylindrical plasma have shed light on the effect of the incompressibility approximation on the spectrum.

Visualisation of 4D Poincare Sections

A powerful technique for the investigation of dynamical systems is the visualisation of successive intersections of orbits with a subspace (the Poincare section) of dimension one less than that of the phase space. These plots can immediately show the presence of chaos, attractors, etc., and are routinely used for two-dimensional (2D) sections. However, the advanced interactive immersive 3D visualisation capability of the ANU WEDGE technology allows the visualisation of 3D sections, or, with the use of colour coding, of 4D sections. This idea has been implemented using Java3D in the WEDGE for the Froeschle map (two coupled standard maps) and will be used to investigate criteria for the existence of KAM tori.

Statistical Mechanics and Quantum Field Theory

The revived question of the completeness of the Bethe Ansatz for the six and eight-vertex models in statistical mechanics was studied and verified for a number of typical problem cases.



A random tiling associated with a solvable lattice model in statistical mechanics

The free energy of the chiral Potts model was shown to be a meromorphic function on a particular Riemann surface with a complete description of its zeros and poles given. Such descriptions play a very useful role in exactly solvable models, and this is the first time this has been done for the chiral Potts model.

The functional equations for excited states in the massive Quantum Field Theory obtained by $\phi_{2,1}$ perturbation of the $M_{3,5}$ model of Conformal Field Theory were studied.

Investigation of the combinatorial aspects of the groundstate wavefunction of loop models continued with a series of new conjectures formulated for the rotor model. The investigation of the magnetic properties of exactly solved quantum spin ladders continued with detailed calculations given for the spin-1 ladder of relevance to the experimental compound BIP-TENO. Probabilities for random walkers to be absorbed at the ends of a number of lattice tubes, including the square, triangular and honeycomb lattices were also derived. The problem on the triangular lattice was previously considered to be intractable. These results may apply to the physics of carbon nanotubes.

Nonlinear Physics Group

Research Accomplishments

The Nonlinear Physics Group is engaged in fundamental research on nonlinear phenomena and the dynamics of nonlinear localised modes, guided waves, and solitons in various branches of physics. The interdisciplinary research of the Group covers several topics such as nonlinear effects in optical bulk media and optical fibers, all-optical switching devices, nano-optics and photonic crystals, self-trapping effects and energy transfer in condensed matter physics and biopolymers, nonlinear atom optics and matter waves including the dynamics of the Bose-Einstein condensates.

2002 was, for many reasons, a very special year for the Nonlinear Physics Group. The first international meeting of the Sir Oliphant Conference Series with over 100 participants, the first Federation Fellowship of the School, two Australian Research Council research grants, and a big share in two recently announced Australian Research Council Centers of Excellence with a total of ~$3M in research support for the next five years are just a few examples of the Group's brilliant performance and achievements in the past year. Along with the long-standing reputation of one of the most active and productive research groups in Australia, the Nonlinear Physics Group becomes one of the most successful in the Australian National University and the School in gaining external funding through the new funding scheme that was introduced last year. We believe that in the coming few years, the Group will expand substantially while playing a leading role in the two Centers of Excellence and gradually evolving into a full-size department of the School. The recent awards would also allow the Group to extend its activities into several novel research directions such as left-handed meta-materials and biophysics, as well as to amplify the quality of research in soliton physics and photonic crystals, as well as Bose-Einstein condensation.

The Group members continued research on optical solitons as part of an international research team composed of members of the Group and the Laser Physics Centre, working on both theory and experiment. These activities have been supported by the appointment of Dr Dragomir Neshev, a former Visiting Research Fellow, as a Research Fellow in a three-year position. Another Visiting Research Fellow of the Group, Dr Anton Desyatnikov, was awarded a Fellowship of the Humboldt Foundation and he is now in Münster, also keeping close contacts with the Group.

The Group plays an active role within the Institute of Advanced Studies, hosting many overseas researchers and research students. In 2002 we continued to work on several novel research directions, including the physics of photosensitive optical materials (in collaboration with the experimental team of Professor Satoshi Kawata from Osaka, Japan). An extensive review paper in the special issue of the Journal of Nonlinear Optical Physics and Materials devoted to Professor A.M. Prokhorov is a result of this extensive collaboration. Additionally, in 2002 we embarked on a new research direction, the physics of left-handed meta-materials, with our new PhD student Ilya Shadrivov as a key player.

The research interests of the Group are expanding each year, and now include areas beyond traditional nonlinear optics and soliton physics, such as linear and nonlinear propagation of light along photonic-crystal waveguides and waveguide bends, nonlinearity-induced folding and self-assembly of biopolymers, the dynamics of nonlinear matter waves, the stability of optical vortices and the dynamics of vortex matter, novel photonic materials and devices. Four distinct research streams can now be identified according to the main interest of the Group's key players: (i) nonlinear optics and optical solitons (Dr A. Sukhorukov and Dr D. Neshev); (2) nonlinear matter waves and Bose-Einstein condensates (Dr E. Ostrovskaya and Ms P. Louis); (3) photonic crystals and waveguides (Dr A. Sukhorukov and Dr S. Mingaleev); (4) left-handed meta-materials and waveguides (Mr I. Shadrivov and Dr A. Sukhorukov). These main directions are interlinked by our wide expertise in nonlinear physics, so that the Group members share many common interests across the spectrum of nonlinear physics research. One of the excellent examples of such collaboration is a number of recent projects devoted to nonlinear waves in periodic media, covered by both the physics of photonic crystals, and the theory of Bose-Einstein condensates in optical lattices.

Nonlinear Optics and Optical Solitons

One of the most important highlights of 2002 is the completion of the book "*Optical Solitons: From Fibers to Photonic Crystals*" by Yuri Kivshar and Govind Agrawal (University of Rochester, USA) which is scheduled for publication by Academic Press in March 2003. The book is the first to provide a thorough overview of different types of optical solitons and their applications. The main purpose is to present the rapidly developing field of optical solitons starting from the basic concepts of light self-focusing and self-trapping. It introduces the fundamental concepts in the theory of nonlinear waves and solitons using physically realistic models of nonlinear optics while also focusing on their stability and dynamics. In addition, it summarises a number of important experimental verifications of the basic theoretical predictions and concepts covering the observation of self-focusing in the earlier days of nonlinear optics and the most recent experimental results on spatial and temporal solitons, gap solitons, vortex solitons, discrete solitons, incoherent solitons, and solitons forming in photonic crystals, and introduces the fundamental concepts in the theory of optical solitons through realistic physical models. The material is based

Professor John Love (left) and Professor Yuri Kivshar (right) celebrate the successful year at the Christmas lunch with their colleagues and students on the authors' years of experience actively working in and researching the field, and provides links with other fields such as the nonlinear dynamics of spin waves and nonlinear matter-waves in the Bose-Einstein condensates.

The most recent activity of the Group is the investigation of the nonlinear light localisation phenomena in the periodic refractive index gratings that are optically induced in photorefractive materials. This experimental and theoretical research is conducted by Dr D. Neshev, Dr A. Sukhorukov, and Dr E. Ostrovskaya, in collaboration with Dr W. Krolikowski (Laser Physics Centre). The study of the physics of propagation and localisation of light in these reconfigurable periodic photonic structures opens up new possibilities for all-optical control and manipulation of light in nonlinear media.

Bose-Einstein Condensates

Two years ago, our Group started research in a completely new and exciting field of Bose-Einstein condensation (BEC). In collaboration with Dr C. Savage from the Faculties (ANU), the Group initiated a number of projects in this rapidly developing area of physics. More recently, the Atom Optics Laboratory in the Faculties, led by Dr J. Close, have produced the first Australian BEC which takes them a step closer to establishing a National Atom Laser Facility in future years. A number of important theoretical results have been produced in collaboration with our Group and will be tested experimentally. Our recent results in this field include the study of BEC in optical lattices. In particular, we analysed the existence and stability of spatially extended (Bloch-type) and localised states of BEC loaded into an optical lattice, and studied the band-gap structure of the matter-wave spectrum in both the linear and nonlinear regimes. We demonstrated the existence of families of spatially localised matter-wave gap solitons, and analysed their stability in different band gaps, for both repulsive and attractive atomic interactions.

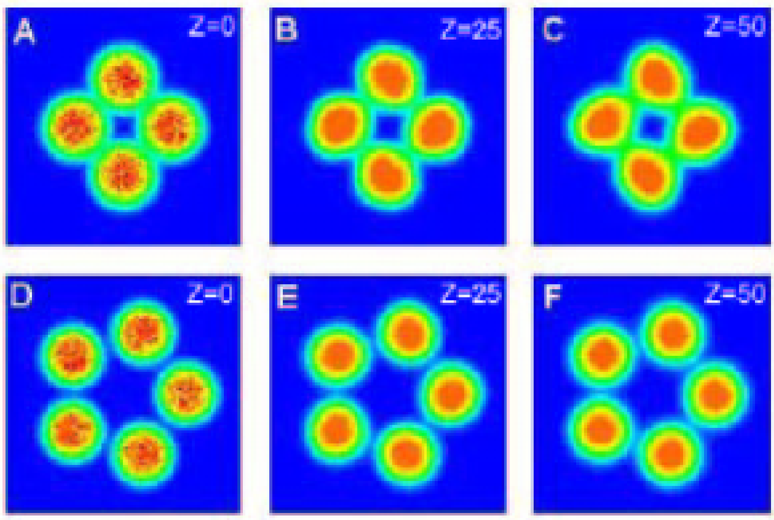
Photonic Crystals and Waveguides

One of our new areas of research continued in 2002 was the study of *nonlinear properties* of photonic crystals and photonic crystal waveguides. Photonic crystals are usually viewed as an optical analog of semiconductors that modify the properties of light, similar to a microscopic atomic lattice that creates a semiconductor band-gap for electrons. It is believed therefore that by replacing relatively slow electrons with photons as the carriers of information, the speed and band-width of advanced communication systems will be dramatically increased, with potential benefits for the telecommunications industry. However, to employ the high-technology potential of photonic crystals, it is crucially important to achieve a dynamical tunability of their properties. This idea can be realised by changing the light intensity in *nonlinear photonic crystals*. Harnessing the nonlinear properties of photonic crystals and photonic-crystal waveguides offers an opportunity to create the all-optical analogs of diodes and transistors that will one day enable the first all-optical computer to be built. One of our important highlights in 2002 was the feature article "Nonlinear Photonic Crystals: Toward All-Optical Technologies" by Serge Mingaleev and Yuri Kivshar published in Optics & Photonic News in July.

Left-Handed Materials

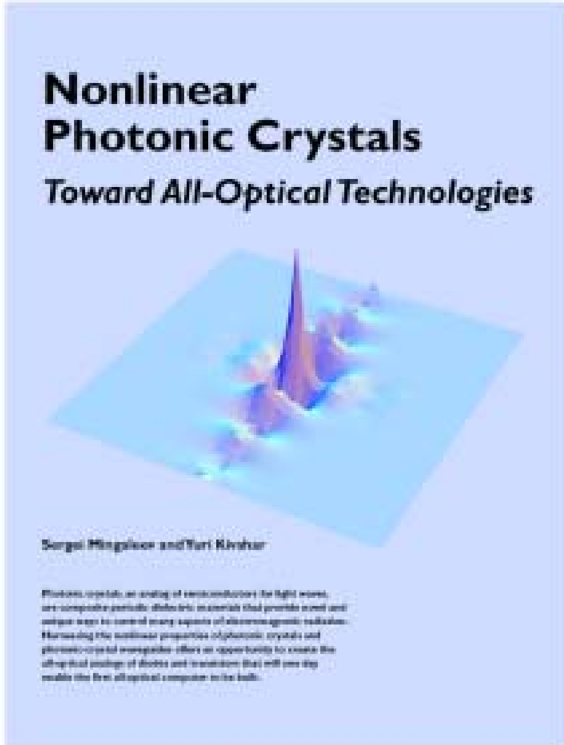
The study of waveguides made of the so-called left-handed materials (LHMs) is a novel direction explored by the Group in 2002. Normally light waves carry energy in the same direction as they propagate, following what is called a right-hand rule. But in 1968 Victor Veselago of the Lebedev Physics Institute in Moscow concluded that if you could tune the properties of a material just right, light would transmit energy one way while undulating in the other. In left-handed materials both the permittivity (basically the response of the material to an external electric field) and the permeability (response to a magnetic field) have negative values. This results in a negative index of refraction — when light falls on a LHM sample it refracts in a direction opposite to that for conventional materials— this "left handed" property makes a LHM a great candidate for a solid state filter or antenna.

The study of the properties of LHM is a current research project of our new PhD student Ilya Shadrivov, who joined the Group in April 2002. In particular, in collaboration with Andrey Sukhorukov, Ilya performed a systematic analysis of linear guided waves propagating in a slab waveguide made of a negative-refraction-index material, i.e. the LHM waveguide. It was revealed that the guided waves in LHM waveguides differ dramatically from conventional waves, and they possess a number of peculiar properties, such as the absence of the fundamental modes, the mode double degeneracy, and the sign-varying energy flux. In particular, the existence of novel types of guided waves with a dipole-vortex structure of the Pointing vector has been predicted.



Clusters of optical solitons predicted and analysed by the group members in 2002


Spatial Optical Solitons
Guiding Light for Future Technologies
YURI S. KIVSHAR and GEORGE I. STEGEMAN



Cover Stories of two issues of Optics and Photonics News in 2002 featuring the research highlights of the Nonlinear Physics Group

Applied Photonics Group

Research Accomplishments

During 2002 the Group has continued with fundamental research in guided wave photonics that relates to the analysis, modelling and design of novel light-processing devices for telecommunications and other applications. These activities have involved collaborative research with theory and experimental groups within the School, within the Australian Photonics CRC in Sydney and Melbourne, and also overseas. The outcomes of these activities include a growing number of patents. Notwithstanding the severe downturn in the photonics industry that has occurred worldwide during the past two years, there is still a significant number of research activities funded through government and commercial links.

The Group continues to play a major role in photonics education and outreach through the presentation of undergraduate photonics courses in the Faculty of Science, the inaugural Korea-Australia Photonics School in Seoul, and the annual Siemens Science Experience for high school students. There are also strong active links with the Photonics Institute in Canberra and with the Canberra Institute of Technology. Advice is also provided to the ACT government in research and education through its Knowledge Based Economy Board.

Hydrogen-Free Planar Waveguides & Devices

In collaboration with the Space Plasma and Plasma Processing Group in PRL, a new range of doped silica-based materials is being developed in thin-film form using the HARE PECVD reactor. These materials are in principle hydrogen-free, which should avoid the high optical transmission loss at 1400 nm that is prevalent in existing materials due to OH-ion absorption. Rib waveguides have been fabricated and their propagation characteristics measured, including comparison with numerical simulations of their modal fields.

Segmented Gratings

Contemporary grating-assisted wavelength add/drop filters for single-mode transmission systems either reflect light back along the fundamental mode or into the second or third mode. But even in the latter case, it is difficult to completely suppress reflection into the fundamental mode. A new class of gratings — the segmented grating — possesses specific symmetries in the waveguide cross-section that totally suppresses back reflection into the fundamental mode. The design has been patented.

Transition Loss in Bent Waveguides

When a fibre or waveguide enters a bend, there is a transition region from no loss on the straight waveguide to a continuum loss on the bent waveguide where a series of discrete radiating beams is observed. The physical mechanisms in the transition region responsible for these beams have never been fully understood, but recent numerical simulations combined with experimental work with single-mode fibres has now provided a more complete understanding.

Solitons

A number of developments included a new mathematical method for the easy analysis of cellular automata with interactions covering several neighbours and allowing for many levels. Our work on multi-soliton complexes considers solitons with many components in materials with a slow response. A chapter on this topic was completed for an American Mathematical Society book. Also, exact soliton solutions of the quintic complex Swift-Hohenberg equation, which is an important equation in determining pattern formation in dissipative systems, have been derived.

Optical Sciences Centre

Research Summary

Traditionally, nonlinear optics, solitons and light-guiding-light phenomena form the mainstream of research at the Optical Sciences Centre. Fundamental research is always our priority, so we are mostly developing ideas and concepts. One of the central ideas, namely the notion of the soliton, created a revolution in twentieth century mathematical physics. It is a notion from the theory of dynamical systems with an infinite number of degrees of freedom. We have generalised this notion from being a mode of a fully integrable system to being a mode of a Hamiltonian system, and have gone even further away to consider dissipative systems. We have also introduced the concept of multi-soliton complexes. This generalises the idea of a single soliton to more complicated objects. As an essential part of these generalisations, our research topics include, but are not limited to, a thorough theoretical analysis of optical telecommunication links, laser sources of ultra-short optical pulses, analysis of ultra-fast all-optical switches, planar integrated optic devices, Bose-Einstein condensates and basic principles of classical and quantum optics in general. The research concentrates on the most difficult and deep mathematical aspects of the above physical problems. At the same time, it satisfies the needs of most of the important applications. Nothing is more useful than a good theory. The most important theoretical predictions made in Optical Sciences Center have always been confirmed experimentally. Examples include Fermi-Pasta-Ulam recurrence, photon echo optical memory devices, ultra-short pulse propagation in birefringent optical fibers and various others. Research in such a diverse range of phenomena is done at the forefront of world trends. It is conducted in close collaboration with the leading research groups in Australia as well as around the world. Some of our research projects are done in collaboration with the Laser Physics Center (ANU). Our recent research grants were successfully achieved in collaboration with groups at the University of Sydney and the University of New South Wales. These relate to a multilevel soliton optical time division multiplexing (OTDM) dense wavelength division multiplexing ultra-high bandwidth transmission system and multi-component pulse generation and propagation in optical fibres. We also have grants from the US Army Research Office related to four-wave mixing in dispersion-managed optical fiber links and the modelling of active optical systems with nonlinear amplifiers. The goal of this research is to reach the ultimate limits of high-bit-rate all-optical information transmission. We have collaborative research projects with the University of Colorado, University of Central Florida, Instituto de Optica (Madrid), Los Alamos National Laboratories (USA), Johns Hopkins University (Baltimore), Kyushu University (Japan), City University (Hong Kong) and many other research organisations around the world. The research results have been reported at the most important international conferences and research workshops and published in the leading scientific journals.

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Robert Robson, BSc Qld, DipMet, PhD, FRMS, FAPS, FAIP (jointly with AMPL)
Michael Simpson, BSc Adel, PhD Newcastle
Susan Scott, BSc Monash, PhD Adel
Irina Talanina, MSc PhD GPI Moscow
Lindsay Tassie, MSc PhD Melb, FAIP
Helge Tverberg, Cand. real. Bergen, PhD UiB, Norway
Guy White, BSc Syd, PhD Oxford, DSc Wollongong
William Woolcock, BSc Qld, PhD Camb, FAIP
Zhang Yu-Shun, Academia Sinica, Beijing, PR China

Departmental Administrators
Mrs Heli Jackson (part time, until November)
Mrs Nyssa Gyorgy-Faul (part-time, until May)
Ms Renee Vercoe (from May)
Ms Wendy Quinn (part-time from May)

Nonlinear Physics Group

Professor and Head of Department
Yuri Kivshar, PhD USSR Acad Sci

Research Fellows
Dragomir Neshev, MSc PhD Sofia (from July)

Postdoctoral Fellow
Elena Ostrovskaya, MSc Mosc, PhD
Andrey Sukhorukov, PhD (from July)

Visiting Fellows
Serge Mingaleev, MS PhD Kiev (until May)
Sergei Kun, MS PhD Kiev (from November)
Oleg Braun, PhD DrSci Kiev (until June)
Dmitry Pelinovsky, Ms Russia, PhD Monash (from December)
Jose Ramon Salgueiro, MS PhD Santiago de Compostela (from September)

Departmental Administrator
Wendy Quinn (part-time from May, full-time from December)

Applied Photonics Group

Professor and Head of Department
John Love, MA Camb, MA DPhil DSc Oxf

Fellow
Adrian Ankiewicz, BSc BE UNSW, PhD (CRC)

Postdoctoral Fellows
Douglas Bulla, (jointly with PRL) PhD Sao Paulo

Visiting Fellows
Satis Arnold, BSc MSc UNSW, Techkne Pty Ltd
Martin Elias, ADC Australia Pty Ltd
Vika Steblina, BSc Mosc, PhD, Bandwidth Foundry
Andrew Stevenson, PhD, BSc UQ, Photonics Institute

Departmental Administrator
Wendy Quinn (part-time from May, full-time from December)

Optical Sciences Centre

Professor and Head of Centre
Allan Snyder, SM MIT, MS Harv, PhD DSc Lond, FAA, FTS, FRS

Professors
Nail Akhmediev, DSc USSR Acad Sci
John Mitchell, BSc Syd, PhD UNSW

Visiting Fellows
D'Andrea Giuliano, US Army Research Office, Far East, USA (August)
Ken-ichi Maruno, BSc Osaka, MSc PhD Kyushu (from June)

Departmental Administrator
Ms Cheryl Morse (until March)
Ms Anita Kuffner (March to June)
Mrs Amanda Greaves (from June)