This has been a year of progress and achievement in the department. It continues to flourish and to be an exciting place to study and work. We continue to attract a large cohort of the cleverest young people into Physics, and to give them a challenging education that they and the external world value highly. We have not rested on our laurels: the degree programmes have undergone an extensive revision this year and a new MSci programme in Theoretical Physics introduced. And its still a fun place to be! The undergraduate body has been very successful in winning awards this past year: the Imperial College Physical Society won the Institute of Physics award for the best Physics Society in UK Universities. Students in the department were very successful in the College Entrepreneurship Ideas Challenge, and a physics team won the top £25,000 prize.

The department continued to work with outside bodies in valuable research collaborations. New links with BP, with the Culham Laboratory and with the Sandia National Laboratories in the USA have been established, and the College has signed a Memorandum of Understanding with the National Physical Laboratory that will enhance research collaborations in a number of areas. The newly-established Exploitation Committee, under Lesley Cohen’s leadership, is exploring ways in which the departmental Intellectual Property can be better used.

A number of new staff joined us this year: we welcome Professor Edward Hinds and Dr Ben Sauer who have joined the QOLS Group from the University of Sussex to establish the Imperial College Centre for Cold Matter. Dr Paul Nandra joined the Astrophysics Group from the Goddard Space Science Center in the USA. Dr Mark Neil and Dr Peter Torok joined the Photonics Group from Oxford University.

The major refurbishment of research laboratories under the Government’s SRIF programme has delivered high quality space for new programmes. We have become used to having an army of contractors working in the place and this will continue for the coming year, but will result in laboratories more fitting for the 21st century.

A number of major projects were initiated in the department, including a Basic Technology programme grant on the generation and application of attosecond light pulses and a DTI Beacon Award to Professor Paul French to develop fluorescent lifetime image technology for biomedical applications. The department's contribution to e-Science and the GRID has continued to flourish.

Members of the academic staff garnered a number of important awards and prizes during the year, reflecting the high standing they are held in by the outside world. Professor Gareth Parry was elected as a fellow of the Royal Academy of Engineering. Professor Arkady Tseytlin was awarded a Royal Society Wolfson Merit Award, a highly prestigious award intended to retain research stars in the UK. Dr Ralf Toumi was awarded the £50,000 Philip Leverhulme Prize in recognition of his research in atmospheric physics. A team from the Physics and Computer Science Departments won top prize in the Supercomputer 2002 Conference in the USA for their project on real-time genome sequence to gene function analysis. Professor Peter Cargill was awarded a PPARC Senior Fellowship for 3 years and Dr Almut Beige was awarded the James Ellis Research Fellowship of the Royal Society to pursue her work on quantum computing and quantum cryptography.

To end on a sad note, I am sorry to say that Professor Tony Stradling died a few weeks after his retirement from the College. A memorial service was held to commemorate his life and achievements in Oxford Cathedral, attended by many present and past members of the department who remember an outstanding colleague with great affection.

P. L. Knight FRS
Head of Department
April 2003
For contact addresses
see page 49
Undergraduate and Postgraduate Studies

Undergraduate Teaching
(Queries about undergraduate admissions should be addressed to the Admissions Tutor)

Schools Liaison http://www.imperial.ac.uk/options/ Page 40

Postgraduate Studies - Page 41

MSc
Prospective postgraduate students interested in admission for an MSc course should contact the appropriate course organiser listed below.

- MSc in Optics and Photonics
  Dr. K. Weir, Tel: 020 7594 7723, Fax: 020 7594 7714, e-mail: k.weir@imperial.ac.uk

- MSc in Quantum Fields and Fundamental Forces
  Dr. J. Halliwell, Tel: 020 7594 7831, Fax: 020 7594 7844, e-mail: j.halliwell@imperial.ac.uk

PhD
Those interested in admission for doctoral level research leading to the PhD degree should contact the Heads of Research Groups in subject areas of interest as listed opposite. The Director of Postgraduate Studies will be glad to advise on all general matters concerning the requirements for admission as a postgraduate student.
Search for Dark Matter Particles

Parts manufacture for ZEPLIN III, our next generation two-phase xenon detector for dark matter search, is now 80% complete. This will be used to search for signatures of direct interactions of exotic new particles in the Boulby underground facility.

Meanwhile the UKDMC collaboration has deployed a simpler single phase liquid xenon scintillation target, ZEPLIN I. This uses a pulse shape discrimination technique, and, after only a few weeks operation, has produced the best results in the world (Figure 1). These new results now cast very serious doubt on earlier claims by a group based in Rome to have detected the dark matter particles at higher interaction strengths (green contour in the figure). Our new results are an upper limit and the dark matter particles must be below it. ZEPLIN III should achieve about 2 orders of magnitude better sensitivity within a few years and this will maintain our world leading position, and pave the way for larger targets with up to 1 tonne of xenon.

Gravitational Wave Astronomy

The detailed design of the Charge Management System for the SMART-2 technology precursor satellite to gravitational wave science mission, LISA, of the European Space Agency is complete (Figure 2). We are developing an Engineering Model of the system. This system is required by LISA to control the charge build-up on the isolated proof-masses, which form the mirrors for the large baseline interferometry between the three spacecraft in the constellation. Charge build-up is caused by cosmic-ray impacts on the spacecraft and proof masses. New analyses of the way in which the charge is deposited, using the latest version of GEANT4 have shown that this effect may be more severe than previously thought, and a new contract has just been agreed with ESA to continue this work.

Gravitational wave astronomy from space was highlighted as a high priority area for PPARC funding in the recent Government spending review.

Neutrino Astrophysics

The Astrophysics Group has formally been accepted into the AMANDA and ICECUBE collaborations. Our scientific interest is in the connection between neutrino emission and gravitational waves, which would be expected in some of the more extreme forms of collapse/explosion of astrophysical objects.

Studies of Stars and Supernovae

J. E. Drew, W. P. S. Meikle, L. Lucy, Y. Unruh, R. Kotak, M. Pozzo, S. Sim, and J. Vink

Young stars

The problem of how the late accretion phase of young stars depends on stellar mass continues to be explored using high resolution spectropolarimetry – a technique that provides insight into the geometry of the circumstellar environment on scales significantly smaller than direct imaging can reach. This year, a study of the intermediate-mass Herbig stars was completed and published. We found a marked change in the character of the linear polarization observed across Hα (a bright hydrogen emission line) between the generally cooler, lower-mass...
Herbig Ae stars and hotter, higher-mass Herbig B stars. Our result reinforces already suspected similarities between Herbig Ae stars and the lower mass young stars commonly known as T Tau stars. This finding has been followed up with the first high-resolution linear spectropolarimetry of T Tau stars.

We also work on Doppler reconstructive imaging of the surfaces of T Tau stars using high resolution spectroscopic time series. T Tau stars are complex objects: the mass accreted from their circumstellar disks onto the stellar surface via magnetic loops. The indirect imaging aims to better understand the accretion and the role of magnetic fields in such stars. Surface images obtained of the T Tau star, SU Aurigae, show that features can change on very short time scales (roughly one rotation period) and that variability is present that cannot be explained as due to either cool or hot star spots. This suggests Doppler images of T Tau stars derived (as is commonly done) from line profiles observed over several rotation periods should be treated with extreme caution.

**The Sun as a star** Knowledge of long-term variations of the solar brightness is an important input to studies of the Earth’s climate change, especially when trying to isolate man-made contributions. We have taken an important step towards accurate modelling of solar variability, by showing that brightness changes between solar cycle minimum and maximum can be attributed solely to changes in the surface coverage of dark and bright magnetic elements. We have started to apply our knowledge of solar variability to other Sun-like stars within the framework of the Corot asteroseismology and planet-finding mission.

**Core-collapse Supernovae** In our study of SN 1987A we concluded that the dramatic slowdown in the decline of forbidden lines indicates that excitation of the ejecta at very late times is driven by the radioactive decay of $^{44}$Ti. We obtained strong evidence for dust condensation in the ejecta of the core-collapse SN 1998S, strengthening the belief that supernovae are major sources of interstellar grains. However, some dust may also have formed in the progenitor wind. We continued our IR observational programme aimed at detecting core-collapse supernovae in the dusty nuclear regions of starburst galaxies. One candidate supernova has already been found. See http://astro.ic.ac.uk/Research/Stellar/Supernovae/NSN/images.html.

**Thermonuclear Supernovae** Our investigations of thermonuclear (type Ia) supernovae via early-time spectroscopy continued under the umbrella of the Type Ia Supernovae EU Research Training Network. We are one of the two main observational groups involved. Late-time spectroscopic work also continued with the completion of our first multi-zoned spectral model for type Ia supernovae. Our joint programme with Liverpool John Moores University made good progress with the completion of the SupIRCam infrared camera for the new robotic Liverpool Telescope. Observations with it, starting in 2003, will test for systematic bias (due to intervening dust) in the use of Type Ia supernovae as cosmological distance indicators.

**Hα emission line stars** We have established and are the UK lead in a long-term collaboration to carry out a deep spectroscopic survey of the southern Galactic Plane for Hα emission line stars. The high sensitivity of the imaging provided by the now-complete AAO Schmidt Hα imaging survey (See Figure 3) picks out candidate emission line objects down to a faintness limit that promises a factor of 100 expansion of existing catalogues of emission line stars. This is an important opportunity because Hα emission is a marker for just those late and early stellar evolutionary stages that remain poorly understood – mainly because so few examples of key object types are yet known.

**Numerical modelling** Activity has centred on developing numerical radiation transfer techniques. Previous work on transition probabilities for Monte Carlo energy packets has been extended to treat interactions with the thermal pool of free electrons. This then allows the ‘macroatom’ statistical sampling formalism to be used to obtain NLTE solutions for stratified atmospheres. In parallel, we are developing an algorithm using these techniques that is designed to facilitate generalisation to multi-dimensional media. These developments will enable realistic modelling of the spectra of a wide range of astrophysical environments.

**Cosmology and Extragalactic Astrophysics**


**Infrared and submillimeter surveys** With collaborators at Edinburgh, Cardiff and Durham, the Group has embarked on a new survey of 0.5 square degrees of the sky (SHADES) at 850 microns with the James Clerk Maxwell Telescope (JCMT). Results from their earlier survey of 200 square arcminutes of sky were published during the year, demonstrating that most submillimetre sources are high

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**Figure 3. Star fields and Hα nebulosity in Vela - field 459 from the AAO UK Schmidt Hα Southern Galactic Plane Survey (http://wwwfau.roe.ac.uk/sss/halpha/index.html). This is just one of the 234 4′ × 4′ fields imaged, available for spectroscopic follow-up.**
redshift star-forming galaxies. The galaxies are surprisingly strongly clustered. The Group has also carried out a study, using data from the Hubble Space Telescope, of host galaxies for high redshift supernovae. Several of the galaxies appear to be undergoing interactions and seem similar to the star-forming galaxies found in infrared surveys. A search for dust in these galaxies has been started using the JCMT.

Preparations have continued for the SWIRE Legacy Survey to be carried out with NASA’s Space Infrared Telescope Facility (SIRTF), due for launch in April 2003. This is the largest survey project being carried out by SIRTF and is expected to yield over a million infrared galaxies, in the wavelength range 3 to 170 microns. Rowan-Robinson (Deputy PI) leads the SWIRE science program.

With collaborators at Kent, Sussex and Groningen, the group is preparing the data analysis pipeline for the Japanese all sky far infrared survey mission, ASTRO-F, due for launch in March 2004. The group leads the Framework 5 EC TMR Network, ‘Probing the Origin of the Extragalactic background radiation (POE)’ involving 20 European groups.

Cosmology The Astrophysics Group, continues its involvement in the MAXIMA and BOOMERANG experiments, measuring the anisotropy of the cosmic microwave background (CMB) radiation. The BOOMERANG consortium completed the final analysis of the anisotropy power spectrum, and the measurement of cosmological parameters, from the current data. MAXIMA data were used to observe and characterise emission from intervening astrophysical sources of microwaves, both in the Milky Way and in distant galaxies. Both teams have also begun to prepare for new data observing the polarisation of the CMB radiation.

We are also involved in an ongoing project to determine the gravitational radiation from super-massive black holes (up to a billion times the mass of the sun) in the centres of galaxies. With Don Backer, we have published a study showing that such gravitational radiation may be detectable using observations of millisecond pulsars, more accurate than any terrestrial clocks. This work involves calculations of the formation of galaxies, the dynamics of the black holes, and the detection of gravitational radiation.

Gravitational Lensing We have developed a new method for the inversion of images of gravitational lenses, that is faster and more accurate than previous methods. A galaxy or galaxy cluster can act like a lens, distorting and magnifying the image of the source galaxy. As illustrated in Figure 4, the ‘semi-linear’ inversion method solves simultaneously for the light profile of the source, and the mass density profile in the lens, that recreates the image seen. The method is now being applied to Hubble Space Telescope images of lens systems to investigate the dark matter profiles in galaxies and galaxy clusters.

X-ray astrophysics We have used observations with the Chandra x-ray observatory of Lyman-break galaxies in the Hubble Deep Field North, to provide the first x-ray constraints on star formation at high redshift. The results are in remarkable agreement with UV measures, and indicate that future, deeper views of the x-ray universe will be dominated by starforming galaxies. We have also completed the analysis of a new, large-area hard x-ray survey with the ASCA satellite. The results shed new light on the nature of obscured AGN, and, in particular, bring into question the applicability of standard AGN synthesis models.
The science of complex systems is highly interdisciplinary. It deals with dynamical systems composed of many interacting parts. Methods from statistical mechanics are employed to gain insight into the behaviour of such systems. The overall objective is to address why nature is complex, not simple, as the laws of physics seem to imply.

We demonstrate how, from the point of view of energy flow through an open system, rain is analogous to many other relaxational processes in Nature such as earthquakes. By identifying rain events as the basic entities of the phenomenon, we show that the number density of rain events per year is inversely proportional to the released water column raised to the power 1.4. This is the rain-equivalent of the Gutenberg-Richter law for earthquakes. The waiting times between events is also characterised by a scaling region, where no typical time scale exists. This is the rain-equivalent of the Omori Law for earthquakes. All of our findings are consistent with the concept of self-organised criticality, which refers to the tendency of slowly driven non-equilibrium systems towards a state of scale free behaviour.

The de Broglie waves associated with the electrons in molecules and solids scatter from the atoms and interfere, enhancing the electron density in some places and reducing it in others. This quantum mechanical effect plays an important role in chemical bonding and contributes to interatomic forces, which cannot be understood using classical physics alone. To simulate chemical reactions accurately, it is necessary to use quantum mechanics. Most quantum mechanical simulations replace the electron-electron interactions by a simple effective potential or mean field. The simplest approximation of this type, the local density approximation, assumes that the exchange-correlation hole surrounding each electron is the same as in a uniform electron gas. As can be seen from Figure 1, this is not a good assumption. Other mean-field approximations are somewhat more realistic, but they have not proved accurate enough to study chemical reactions reliably and consistently.

The Quantum Monte Carlo (QMC) methods we use, which solve the full Schrödinger equation including electron-electron interactions, are at least an order of magnitude better. This year we are focussing on two main projects. The first is to carry out QMC simulations, incorporating a new and sophisticated treatment of finite-size errors, of the surface energy of the uniform electron gas, the value of which has been the subject of a long standing controversy. A precise calculation of the surface energy as a function of density will provide an important benchmark for other theories and serve as a stepping stone towards simulations of more realistic surfaces. Our second project is to calculate exchange energy densities in a wide range of many-electron systems. This will allow us to test existing approximations and, we hope, derive better ones for use in density-functional calculations.

When we put together a large collection of atoms or electrons, order may emerge from their complex cooperative behaviour. A central challenge in condensed matter physics is the question: "how does the sum become more than its parts?" Theoretical progress in understanding such
"emergent phenomena" can help us search for, and even design, new materials of practical importance. Examples include superconductivity and ferromagnetism. The question is how these exotic phases of matter might emerge from the interplay of quantum interference, strong interactions and disorder. Cuprate superconductors have caused much excitement in the last decade because they do not have to be cooled to extremely low temperatures to become superconducting. Strangely, they are far from ordinary metals even in the resistive state at room temperature. I have been working on a gauge theory of this strongly correlated quantum system. A key prediction of our picture on the optical properties of the cuprates has recently been tested in experiments - our results are consistent with the experimental findings. Decoherence in quantum Hall ferromagnets consists of two parallel two-dimensional electron gases in a strong magnetic field. These layers are in close proximity on the atomic scale in a GaAs hetero-structure. The Coulomb interaction between the electrons in the two layers drives a quantum transition to an ordered state, akin to a ferromagnet (where all the magnetic moments point in the same direction). A simple theory would typically state that any attempt to detect which of 2 paths is taken by an electron will result in the destruction of the interference processes. We have considered a system consisting of a dot on a spring or cantilever which can move between 2 contacts. Transport can occur either by resonant tunnelling or by shuttling, where one electron per cycle is carried from one contact to the other. If the potential difference across the system is larger than the oscillation frequency the cantilever may be driven by excitation by the electrons themselves. The behaviour is very sensitive to the mechanism for dissipation of the mechanical energy: something which is badly understood. An Aharonov-Bohm ring is a realisation of Young’s slits for electrons in a solid. Quantum mechanics textbooks typically state that any attempt to detect which of 2 paths is taken by an electron will result in the destruction of the interference processes. We have considered a system consisting of an Aharonov-Bohm ring coupled to a charged cantilever (see Figure 2).

In a simple picture the state of the cantilever can only be changed if an electron goes round its side of the ring; the interference fringes should then be destroyed. Surprisingly this is not the case: the state of the cantilever can change while preserving the interference. It appears therefore that a fundamental tenet of quantum mechanics has been broken. However, the effect can be explained in terms of interference close to the cantilever; far from contradicting basic quantum mechanics it confirms it. What happens when the components of a simple classical machine become very small? We have studied a system of gears and derived the quantisation rules for the states of such a system.

We have developed a transfer matrix like method for 1D disordered interacting systems. Spinless fermions show a metal-insulator transition for attractive interactions, in contrast to non-interacting systems for which all states are localised in both 1 and 2 dimensions. The method can be extended to other models and to systems of finite cross-section; an essential first step to studying 2 and 3 dimensional systems.

Due to the increased interest in spintronics, the use of a spin polarised current, much effort has been expended in the design of devices which can produce such a current. While many of these use magnetic materials, some designs make use of the Rashba effect which associates a splitting of the degeneracy of the spin states with the built in electric field in an asymmetric structure. While studying the electronic properties of the unusual semiconductor junction GaSb:InAs we noted an unexpectedly large spin splitting in symmetric quantum wells. We have now been able to show that the lack of inversion symmetry in the structure of these materials and the strong spin-orbit coupling in such heavy atoms suffices for the spin-splitting and that the asymmetric device structure is unnecessary.

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wavelength structure and for its activity relies on the surface modes induced at the interface between materials with positive and negative dielectric function, or permeability. This structure, which may be an a scale of nanometres, allows us the apply the materials to situations where the electromagnetic field structure is on a length scale much shorter than the wavelength of light i.e. to the near field. This year we have extended our concept of the perfect lens: a lens whose resolution is not limited by the wavelength of light. We have shown that there are several alternative designs for the lens, some of which give very much better performance than the original slab of negatively refracting material. A strong feature of our programme is the large number of collaborations in which we are engaged: several major laboratories in the USA funded by a MURI award, and collaborators in Europe funded by the CEC. We also collaborate with several other departments in the College: Mechanical Engineering on simulation of novel optical materials, and with the Robert Steiner Magnetic Resonance Unit group at the Hammersmith. This latter collaboration has led to the design of a ‘magnetic endoscope’ for the RF fields employed in MRI. Figure 3 shows the endoscope imaging an RF field with a resolution of 1cm - three orders of magnitude greater than the RF wavelength of 15m. The device exploits a new metamaterial which behave like a magnetic wire conducting a magnetic field from one side of the sample to the other.

Figure 3. Our new “magnetic wires” transfer the magnetic field from one side of the device to the other. Here we image a magnetic field in the form of an ‘M’. Left: schematic arrangements. Right: experimental results obtained by Mike Wiltshire (Imperial) and David Edwards (Oxford).
Head of Group:
Professor D.D.C. Bradley

Our programme of research covers most aspects of modern experimental solid state physics including molecular electronic materials, soft condensed matter, quantum optics and photonics, magnetism, superconductivity and inorganic semiconductors. There is a strong emphasis on novel materials and structures and on applications in a wide range of devices. Selected examples of current interests include next generation thin film solar cells (using inorganic semiconductor quantum wells, nanostructured oxides and organic semiconductors), optical microcavities (weak and strong coupling structures and their photonic properties), quantum optics in solids (electromagnetically induced transparency and quantum light sources), ultrafast photonics for telecommunications (sources, amplifiers, optical routers and switches), quantum dots (as novel gain media and for extended wavelength range light emitting diodes (LEDs)), spectroscopic studies of soft matter (liquid crystals, biomolecules, polymers), metrology for the life sciences (single molecule spectroscopy and microanalysis systems), spintronic devices, High Tc and MgB2 superconductors, Si-SiGe electronics (solar cells and highspeed transistors) and molecular electronic materials and devices (high efficiency LEDs for displays and lighting, TFTs for plastic electronics, and photodetectors).

The Group is strongly linked to the Centre for Electronic Materials and Devices (CEMD), which was established in 1998 to promote interdisciplinary and interdepartmental research in electronic materials and devices. The Centre draws together people from the departments of Physics, Chemistry, Electrical and Electronic Engineering and Materials into a wide range of interdisciplinary projects.

Our activities are classified into three main sections, namely molecular electronic materials and applications, transport and magnetism, and semiconductor optoelectronics.

### Molecular Electronic Materials and Applications

#### Dye Sensitised and Organic Solar Cells


Solar cells based on molecular electronic materials rely on charge separation at the interface between an electron-accepting and electron-donating material. Light generated excitons are dissociated to yield separated charges that travel to the electrodes to yield a photocurrent. Structures where the two phases interpenetrate to create a large interface area are desirable and we are studying a range of such ‘distributed heterojunctions’ based on polymer/polymer and polymer/molecule blends as well as dye sensitised systems.

Polymer/molecule blends under study utilise polyarylenevinylene and polyfluorene blended with violanthrone and a soluble C_{60} fullerene derivative, PCBM. In each case the molecule acts as electron acceptor and provides improved electron transport. The influence of blend composition and morphology has been probed via a wide range of experimental techniques. Structural characterisation has used AFM, X-ray and TEM. Photoluminescence quenching, time-of-flight [TOF] photocurrent, electroabsorption spectroscopy, and J-V measurements under dark and light conditions were all used to probe generation and collection of photocarriers. Film morphology, especially in respect of the nature and length scale for phase separation, has proven to be critical to performance. A range of pre- and post-deposition film treatments have thus been used, including thermal annealing and solvent exposure.

In dye sensitised solar cells (DSSCs), light is absorbed in dye molecules attached to the surface of a semiconducting TiO_{2} film. High optical density is achieved using porous nanocrystalline films with a huge surface area. Electrons excited in the dye are rapidly injected into the semiconductor, while the positive ‘hole’ on the dye is removed by a hole-conducting electrolyte. Because the positive and negative charges

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Figure 1. Quantum efficiency spectra of ITO/TiO_{2}/F8T2/Au devices with and without 100 nm of nanocrystalline, porous TiO_{2} between the dense TiO_{2} backing layer and the < 100 nm spin cast Dow Chemical Company F8T2 polymer layer. The increased interfacial area enhances photocurrent quantum efficiency by a factor of five.
are carried to the cell terminals in different materials, the probability of recombination is reduced, and the demands on material quality are much less stringent than for single crystal devices. Power conversion efficiencies of around 10% can be achieved in this way. We have shown previously that electron recombination with the dye cation in DSSCs is rate-limited by electron transport in the TiO₂ film, and can be controlled by varying chemical structure and treatment of the interface. Our recent research has shown that recombination with the hole conducting material, the main loss mechanism in these devices, is also normally controlled by electron transport within the TiO₂. However, at low hole density the diffusion of hole transporting species may be the limiting step. This is particularly relevant to the design of solid state DSSCs, where hole mobility is low, and may lead to resistive losses. We are currently integrating our findings about charge transport and recombination into a device model to interpret solar cell characteristics.

A new experimental topic concerns photovoltaic applications of composites of nanostructured TiO₂ films with conjugated polymers. In this system the polymer sensitises the TiO₂ film, and high optical density can be achieved with much thinner films than for solid state DSSCs. This relaxes the demands on conductivity for the hole transporter. We have shown that very efficient charge separation occurs at the interface between TiO₂ and polymer, and that introducing a porous layer between the dense TiO₂ electrode and polymer increases photocurrent quantum efficiency by a factor of five (see Figure 1). Quantum efficiencies of 15% have been achieved and we are currently studying alternative polymers and device structures to enhance photocurrent generation.

Fundamental research on the mechanisms of charge transport in organic hole transporters and the nature of contacts with metallic electrodes is essential to understand the behaviour of organic solar cells and other devices. We have shown that dark injection transients, can be used to accurately measure the hole mobility in very thin films of conjugated hole transporting materials, and that in materials where hole transport is non-dispersive, the mobility is independent of film thickness. This result is important for photovoltaic and light emitting applications, where device thicknesses are typically 100 nm. Mobility measurements were previously done mainly on ≥ 1µm thickness films using the TOF technique, and the relevance to thin film (≤ 100 nm) devices was uncertain. Electroabsorption has also been used to better understand the nature of interface processes that give rise to electric fields either adding to or opposing the externally applied bias.

Figure 2. A polymer laser in action: Photograph of a red emitting two-dimensional distributed feedback laser. This work results from the Ultrafast Photonics Collaboration with St Andrews University (I. D. W. Samuel and G. A. Turnbull).

G. Heliotis, R. Xia, M. Ramon, M. Pintani, M. Koeberg and D. D. C. Bradley

Semiconducting (conjugated) polymers are now attracting considerable attention as a new materials class for use in electronics and optoelectronics. In addition to many other applications, including full colour flat panel displays, there is increasing interest in developing these materials as optical gain media for lasers and optical amplifiers. In particular, an important future target is the realisation of an electrically pumped polymer solid-state laser diode. We have a programme focussed on (i) detailed characterisation of optical gain and loss properties for polymers with emission in the range 400 - 800 nm and (ii) the fabrication and characterisation of lasers based thereon (see Figure 2).

N. Takada, R. P. F. Oulton, P. Stavrinou and D. D. C. Bradley

Photoluminescence (PL) and electroluminescence (EL) from weakly-coupled conjugated polymer microcavities has been investigated extensively for LEDs and vertical cavity lasers. In this perturbative regime the Fermi golden rule still applies and there is a spectral and spatial redistribution of the emission probability with a resulting, cavity resonance determined, spectrally narrowed, non-Lambertian emission. Recently, however, the non-perturbative strong-coupling regime between exciton and photon modes has also been demonstrated for organic microcavities containing materials such as porphyrins and J-aggregated cyanine dyes but not for conjugated polymers which typically have too large linewidths. We sought to directly address this issue via an initial experimental and theoretical study on microcavities containing ω-conjugated poly(bis(p-butylphenyl)lsilane) [PBPS] (see Figure 3). PBPS has an exciton binding energy E₀ ≈ 500 meV that allows room temperature study of polariton effects. Silicon backbone polymers of this type also have the large oscillator strength and narrow linewidth that is essential to observe strong-coupling: PBPS’ absorption band peaks at 395 nm (α = 129,000 cm⁻¹) and has a FWHM linewidth of 24 nm. Strongly coupled microcavities with PBPS as the active layer show the expected anticrossing between the cavity photon and exciton modes and a giant Rabi splitting of ≤ 430 meV between upper and lower polariton branches at resonance. LEDs have been made with this polymer and strongly coupled structures are under investigation. Novel physical properties, including so-called Boser action (polariton lasing) may also be antici-
We have recently used Raman spectroscopy to study thermal phase transitions in polymer thin films, whose properties provide excellent examples of the competition between surface and bulk interactions. Phase transitions are observed indirectly through their effect on the frequency, intensity, and width of the Raman active modes. An example is shown in Figure 4 where the most intense Raman active mode of polystyrene displays a softening for increasing temperatures (anharmonic interactions) together with a well defined sharp feature at the glass transition temperature. We have been able to show that, in contrast to the situation for polystyrene, there are in fact two glass transitions associated with surface and bulk regions for conjugated polymer films. Understanding these characteristics is important both for improved polymer device stability and fundamental knowledge of the differences between saturated and conjugated polymers.

We have used polarized Raman spectroscopy to probe molecular alignment in conjugated polymer thin films either spin-coated or oriented in their thermotropic mesophase. In particular, we have demonstrated its superior performance over conventional dichroism measurements as a probe of the degree of alignment in thin films. Polarization ratios of up to 80:1 are measured indicating excellent orientation. The superior performance of Raman arises as a consequence of the close association of specific Raman mode tensor components with the molecular axis direction. This contrasts with the dipole-allowed optical transitions that have significant off axis components to their transition moments. The oriented film samples offer exciting opportunities to fabricate polarized emission devices that can be used to backlight liquid crystal displays and through their large birefringence allow dielectric control over propagating modes in amplifiers and lasers.

In addition, the ordering that accompanies orientation is very beneficial to charge carrier transport, with consequent benefits for the performance of FETs, LEDs and photovoltaic devices.

Surface Enhanced Raman Scattering (SERS) has experienced breathtaking progress towards single molecule detection and novel applications at the interface with the life sciences. The study of biomolecules with SERS is in itself not new. However, the depth and breadth of the problems that can be addressed with SERS at the interface with biology have undergone dramatic change, made possible by instrumental breakthroughs. Novel applications in biology include cancer gene detection, spectroscopy of living cells, and single protein/DNA detection. Progress in non-biological applications has been equally spectacular, starting from the pioneering demonstration of single molecule detection, to spectroscopy of single dyes in nanocrystals, or SERS Stokes/anti-Stokes spectroscopy in novel macro-molecules like carbon nanotubes. Our recent progress with single molecule SERS, includes: (i) applications to ultrasensitive chemical analysis (~100 attomolar sensitivity), (ii) single molecule photobleaching, and (iii) dynamic SERS hot-spot phenomena.
An example is shown in Figure 5 where a single rhodamine molecule has been detected in a 0.3 attomole solution after 3 hours of scanning. Attempts to transform this into a standard technique for ultrasensitive chemical trace analysis are under way.

Transport and Magnetism

Measurement of Spin Polarisation in Highly Spin Polarised Ferromagnets using Andreev Reflection Techniques
Y. Miyoshi, Y. Bugoslavsky, R. A. Stradling and L. F. Cohen

We are studying a range of highly spin polarised magnetic materials with the aim of developing hybrid ferromagnetic-semiconductor devices. The spin polarisation of a material can be determined from the degree to which the Andreev reflection from a superconducting tip is suppressed. Experimentally conductance-voltage curves between a superconducting tip and a ferromagnetic metal are analysed as a function of temperature. There are detailed theoretical descriptions that allow for accurate modelling of experimental data. The conductance curves can be well described if four parameters are included: a dimensionless transmission parameter Z that describes the barrier transparency, a smearing parameter G that describes thermal smearing and sample inhomogeneity, the polarisation P (the degree to which carriers are spin orientated in a particular direction), and the superconducting gap D. The method has been used to determine transport spin polarisation of Cu, Ni, and polycrystalline NiMnSb.

MgB2 - a new species of superconductor
Y. Bugoslavsky, A. D. Caplin, L. F. Cohen, L. Cowey, Y. Miyoshi, G. Perkins, M. Polichetti and A. A. Zhukov

After two years of intensive effort, it has emerged that MgB2 may be a fairly conventional superconductor, with the electron pairing mediated by unusually strong coupling with the phonons. However, in one respect it is unusual: There are two superconducting gaps arising from different parts of the Fermi surface.

Carbon incorporation within the base region of Si/SiGe heterojunction bipolar transistors [HBTs] is highly desirable. The growth of Si1-yCy and Si1-x-yGexCy has been studied by RHEED and TPD measurements under conventional GSMBE conditions. The growth rate of the epitaxial films is reduced by the presence of carbon. The dynamic changes in the growth rate during formation of Si1-yCy quantum well structures also provide direct evidence of surface segregation of carbon. The segregation process requires a substantial presence of carbon on the surface. The phenomenological model of surface segregation of Ge has been extended by direct incorporation of growth process parameters into the rate equations. This provided direct insight into the driving forces involved in the segregation process and produced excellent agreement with experimentally observed surface and bulk concentration of Ge. The model is currently being extended to the study of As and C segregation.
The semiconductor optoelectronics section addresses a wide range of physical problems concerning the growth and development of new semiconductor materials (especially III-V systems) and their utilisation in a wide range of devices including resonant cavity diodes, VCSELs, electro-optic modulators and solar cells. Interests include quantum dot semiconductors for data and telecomm applications, single photon source devices for quantum cryptography and solid state quantum optics (electromagnetically induced transparency). Examples of recent projects include:

**Photonic Crystal Technology for guided wave optoelectronics**

S. Klengel, P. Caillaud, C. Palmer, P. Stavrinou, and G. Parry

Photonic bandgap (PBG) structures are materials with periodic regions of high and low refractive index. These 2D photonic crystals have a band structure for allowed photon energies analogous to the electron band structure in conventional semiconductors. Current interests in these fascinating materials focus on using the dispersion characteristics of PBGs to control the propagation of very short (femtosecond) pulses through a photonic circuit. This work is part of the EPSRC funded Ultra-fast Photonics Collaboration (UPC) led by St.Andrews University, a major collaborative programme involving 5 universities and 7 industrial partners. Our efforts cover the theoretical modelling of PBGs and the fabrication and optical assessment of novel structures (fabrication is carried out in collaboration with John Heffernan at Sharp Laboratories of Europe Ltd). Our approach involves the combination of PBG patterns with existing waveguide technology. Single mode, 4.5 µm wide, rib waveguides are typically used as a base for the 2D Photonic circuit, while the PBG structures are generally patterned as a triangular lattice, with holes of diameter ~200 nm and depth ~0.5 µm. The size and separation of the holes determines the location and width of the photonic bandgap. A "defect" can also be introduced in the PBG to create a resonant cavity, as shown in Figure 7(a).

Incorporating active elements in structures poses additional challenges, for example to achieve a full band gap requires the overlap of the TE and TM polarisation band gaps. The width and spectral location of the bandgap is different for TE and TM polarisation and very large fill factor patterns (large holes, closely spaced as shown in Figure 7(b)) are needed to create a spectral region where a full PBG exists. Fabrication issues and tolerances become increasingly demanding, particularly as if in Figure 7(a), the PBG structure is to be combined with existing guided wave technologies.

**Novel Solar Cell Structures**


Our group has pioneered the use of nano-structures in novel strain-balanced, "Third Generation" quantum well solar cells (SB-QWSC). Such cells are expected to generate electricity at twice the efficiency and half the cost of "Second Generation" thin film cells, and are already deployed on satellites. Before the technology can enter the terrestrial solar cell market, costs must be reduced with relatively cheap, light concentrating systems. Our SB-QWSC cell offers significant advantages in high concentration systems. The quantum wells, which are nanometer wide regions of low band-gap semiconductor, absorb low energy photons of light that would otherwise pass through the host cell and thus extend the absorption band-edge of high efficiency GaAs cells to longer wavelengths to generate significant current enhancement while preserving good voltage performance. We have shown that the resulting carriers escape from the well with high efficiency. This leads to extra current at a voltage above that achieved by conventional cells made from the well material, as long as the well material has the same lattice constant as the host cell.

The world’s highest efficiency cells are monolithic, tandem cells formed of GaInP and GaAs. The performance of this tandem is limited by the current produced by the lower band-gap GaAs cell. We have recently demonstrated that were our SB-QWSC to replace the GaAs cell it would increase the world’s highest efficiency tandem from 34% to 36% at around 200 suns concentration. Our current primary research aim is to optimise such tandem cells grown by MOVPE at the EPSRC III-V Facility at Sheffield in collaboration with a leading, European space cell company. We intend to demonstrate the cell in a concentrator system, in collaboration with experts in UK and European universities and an UK concentrator manufacturer.

We are also developing a novel, non-tracking concentrator, which uses the luminescence and quantum confinement properties of quantum dots. We have developed a thermo-dynamic model to optimise concentrator performance, which demon-
strates that separation between luminescence and absorption can be optimised by changing the spread of quantum dot sizes. We are researching the properties of quantum dots, for example their stability, high luminescence efficiency and the possibility of tailoring their absorption edge, which make them good candidates to replace the organic dyes of conventional luminescence concentrators.

We are also applying our strain-balanced cell ideas to thermophotovoltaics (TPV). In this case low-band-gap solar cells are used to convert the radiant energy from conventional power sources directly to electricity. We are collaborating with Italian researchers to design an efficient and environmentally friendly, TPV system to extend the range of Fiat's electric car. In collaboration with B.P Solar we are also studying epitaxially grown films of silicon to investigate the ultimate efficiency that can be achieved by thin film silicon cells. In addition, we have recently extended our fundamental work on the determination of the quasi-Fermi level separation in quantum well systems to the light-biased situation. This work has important implications for questions on the ultimate efficiency enhancement possible with QW cells.

Quantum Optics and opto-electronic devices in the mid-infrared


Quantum optics, i.e. the study of the optical properties of systems where not only the amplitudes but also the phases of the participating electrons' wave functions are under experimental control, is a rich branch of atomic spectroscopy. Effects such as lasing-without-inversion (LWI), ultra-slow light propagation and entanglement are attracting attention for their potential in quantum computation and communication schemes, but are rarely seen in solid-state materials. Now, for the first time, we have seen these effects (Figure 8) associated with "designer atom" intersubband (ISB) transitions in quantum wells, and are progressing towards a LWI demonstration.

The quantum cascade laser features an intense intra cavity radiation field, very strongly coupled to these same ISB transitions, which have sharply peaked absorption spectra. This results, uniquely, in a laser that operates between states that are "dressed" by the laser radiation, allowing for the violation of the standard Einstein population inversion arguments for laser operation. In a new programme, we are studying this effect spectroscopically, using a resonant optical frequency mixing scheme, to probe these "dressed" states inside the laser diode via the resonant structure seen in THz sidebands produced on a separate "carrier" laser. Sideband signals are just appearing, and, because of its promise as an efficient all-optical wavelength converter for optical fibre telecommunications, the College has filed a patent on the device idea.

Figure 8. Electromagnetically-induced transparency (EIT) in a quantum well. A laser tuned to \( E_{23} = 128 \text{ meV} \) establishes a phase relationship between matter-wave states \( \left| 2 \right\rangle \) and \( \left| 3 \right\rangle \). Now, when the electrons (in state \( \left| 1 \right\rangle \)) absorb light, destructive "matter-wave interference" makes the sample transparent at a surprisingly sharp and completely different (177meV) photon energy.
Head of Group:
Professor P. J. Dornan

Members of the Group exercise significant influence in many of the current and future international experiments that investigate the fundamental particles and the forces between them. A primary aim is to address basic questions such as the origin of mass and the observed asymmetry between matter and antimatter. Much of the programme is directed at discovering where the Standard Model, that has proved amazingly successful in the description of electro-weak interactions, will break down, since theoretical expectations imply that it cannot be the final story. This will be accomplished by testing predictions to high accuracy and looking for phenomena outside the model such as supersymmetry and dark matter.

The CMS (Compact Muon Solenoid) experiment, shown in Figure 1, is a general purpose detector being constructed at LHC. The Group has major roles in the detector design and construction, as well as the scientific management of the project.

The Group is active in the electromagnetic calorimeter (ECAL) and the charged particle tracking system. In the ECAL electron and photon energies are measured by their interactions in lead tungstate crystals read out by avalanche photodiodes or vacuum phototriodes. In the last year we have been making precise measurements of the uniformity of the light collection along the length of the crystals using a hybrid photomultiplier device. It has been shown that the uniformity of most crystals is sufficient and a technique has been developed to improve the uniformity of those that fall outside the required limit. A new project is the design of a new amplifier for the electronic readout system.

The CMS tracker is a very large silicon detector system, which is an area where we have two decades of experience. Charged particles are measured by their bending in the 4T magnetic field using finely segmented microstrip detectors read out with low noise and radiation hard APV25 pipeline chips. The APV25 was developed by Imperial College London and Rutherford Laboratory and is based on commercial 0.25 µm CMOS technology.

Recent work has concentrated on complete characterisation of the CMS readout system. Data were taken in a CERN pion beam with the same 40 MHz radiofrequency structure to the highest energy machine in the world, opening a new window of discoveries in particle physics. In particular, it is expected that the elusive Higgs boson, which is the means by which the quarks and leptons in the Standard Model obtain their masses, will be identified.

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Another Imperial-Rutherford Tracker project now at an advanced stage is the development of off-detector digital processing electronics (Front End Drivers) which digitize the APV25 signals and reduce the data volume of 1-2 TByte/s by several orders of magnitude.

High Energy Physics
http://www.imperial.ac.uk/research/hep
At a hadron collider the trigger (real-time selection of wanted events) is critical due to the very large QCD background. The Imperial D0 group is now the largest single group at Level-3 (the highest level trigger), concentrating in particular on tracking. Current activities include commissioning the overall system, the development of track and vertex triggers and the development of ‘b-tagging’ algorithms, used to identify jets containing b-quarks. Another critical area is the understanding of the energy scale of the jets of particles produced after the proton anti-proton collision, and the optimisation of the jet mass resolution. The D0 Jet Energy Scale group is co-convened by an Imperial person and considerable group effort is committed to this area.

Two of the main physics goals in the new run will be B-physics and the search for the Higgs boson – the elusive particle which is responsible for giving mass to all we see around us. The Tevatron produces some trillion B mesons per year allowing us to study CP violation, rare decays and the ways b and anti-b quarks mix. Results are already being produced (Figure 3 shows the B-lifetime as measured by Imperial College personnel) and effort will focus now on B-mixing.

Activity is also already well underway for the longer term goal of finding the Higgs. Within two years we will be able to answer whether LEP did see the first hints for a Higgs at around 115 GeV, before extending the sensitivity to ~180 GeV in the following years.

Experiments to measure CP violation in High Energy Physics

There is no evidence for significant quantities of antimatter in the visible universe, yet any plausible theory of cosmology requires initially equal amounts of matter and antimatter. CP-violation in the interactions of elementary particles could provide the key to understanding this puzzle.

**BaBar**


The BaBar detector is located at the PEP-II electron-positron collider located at SLAC in California. It is dedicated to the study of CP violation using B mesons. BaBar made the first observation of CP violation in B decays in 2001 through the measurement of the parameter sin2β of the CKM matrix. Using increased statistics, this measurement has since been improved to better than 10% precision. Figure 4 shows the current status of knowledge of the “Unitary Triangle” of the CKM matrix, where β is one of the internal angles.

The Group is heavily involved in studies of CP violation in charmless hadronic B decays. These decays are sensitive to a different CKM parameter, namely sin2α, where α is another angle of the triangle.

**LHCb**


The LHCb experiment is an experiment for at LHC specifically designed to study B-mesons to the ultimate precision. The aim is to provide measurements of CP-violation with the highest sensitivity and to look for new physics beyond the Standard Model.

For the CP-violation studies particle identification is required to identify the flavour of the quarks participating in the B-decay. Particles of a known momentum travelling through a medium with velocity greater than the speed of light in the medium emit photons at a fixed angle depending upon the mass of the particle. By imaging the emitted photons onto a plane they will form rings where the radius identifies the mass of the particle. In LHCb this is done with two Ring Imaging Cherenkov Detectors, RICH1 and RICH2.

To improve the projected performance of LHCb the experiment design went through a substantial re-optimization of its tracking and magnetic field configuration in 2002. The implications for the RICH1 detector were large and the Group is responsible for advancing the redesign from a conceptual idea to a full design that satisfies demanding criteria.

**ZEUS**

C. Foudas, A. Jamdagni, F. Metlica, K. Long and A. Tapper

The HERA collider in Hamburg is a microscope used by the ZEUS detector to look deep inside the proton. A 27.5 GeV electron collides with one of the quarks inside a 920 GeV proton, splitting the proton and throwing out debris that can be detected. The proton structure is studied together with the nature of the strong force. The Group has provided key pieces of ZEUS, which it helps run and maintain.

The Group has made leading contributions to the analysis of neutral and charged current events. We have measured the neutral and charged
current cross sections in both electron-proton and positron-proton scattering. The results are shown in Figure 5 where the cross section is plotted as a function of the momentum-transfer in the collision squared. We have also taken an important role in the investigation of both real- and virtual-photon structure as well as studying jet production in deep inelastic e+p scattering.

From June 2003 HERA will run with high intensity polarised electron and positron beams. We shall measure, for the first time, the polarisation dependence of the neutral and charged current cross sections and use the data to search for physics not described by the SM. Crucial to this programme is a precise measurement of the lepton beam polarisation. We have taken the lead in the development of a position detector that will allow the required precision to be obtained.

![HERA 1 high Q^2](image)

**Figure 5. The ZEUS measurement of the neutral and charged current deep inelastic scattering cross sections.** The fact that the four cross sections have equal magnitude at high values of Q^2 is a result of the unification of the weak and the electromagnetic force.

**Neutrino Experiments**

E. McKigney, A. Jamdagni, K. Long, P. J. Doman and W. G. Jones

The neutrino has long been thought to have no mass and to occur in three distinct flavours. This assumption has been built into the Standard Model. However, recent experiments have shown that neutrinos have mass and that neutrinos mix. The consequences of these observations are far reaching; not only do they imply that neutrinos form a significant part of the 'dark matter' known to exist in the universe, but they give rise to the possibility of CP-violation in the lepton sector.

There is a worldwide consensus that the tool of choice for the study of the properties of the neutrino is a Neutrino Factory: an intense neutrino source based on the decay of a stored muon beam. The Group personnel have played key roles in establishing the physics case for a Neutrino Factory and in defining the machine and detector R&D programme for the UK. The present focus of this programme is the international Muon Ionisation Cooling Experiment (MICE). MICE seeks to demonstrate a novel technique by which the phase-space occupied by a muon beam is reduced by passing it through a lattice of absorbers followed by accelerating RF-cavities. We proposed the scintillating fibre tracker that forms the baseline instrumentation for the MICE spectrometers. A crucial input to the MICE experiment is the precise measurement of the scattering distributions of muons as they pass through matter. We have played a leading role in the MuScat experiment that will measure these distributions.

**Calice**

D. Bowerman, W. Cameron, P. D. Dauncey, D. J. Price and O. Zorba

Over the last few years, a worldwide effort has started building towards a high energy electron-positron linear collider with a centre of mass energy in the range 500-1000 GeV. Assuming the Higgs is discovered at the LHC, the linear collider will allow precision measurements of any Higgs (or SUSY) particles in this mass range as well as having a significant discovery potential of its own.

The calorimetry for a detector at the linear collider needs to be able to reconstruct jet energies with resolutions exceeding anything previously achieved if it is to fulfill the physics potential of the machine. The Calice collaboration has been formed to study both electromagnetic and hadronic calorimetry for a linear collider detector. The Group joined the collaboration in 2002 and is designing the readout electronics for a prototype high-granularity electromagnetic calorimeter. The aim of the collaboration is to test this prototype in a beam in 2004.

**Technology Transfer Activities**

J. Hassard, J. Harford, C. Lee, P. Martin, M. Richards and D. Sideris

Our main focus has been in transferring particle physics techniques, technologies and approaches to high throughput discovery systems. We have devised a core platform technology capable of using algorithms sufficiently precise to gain back the factor of approximately 107 signal lost by removing radioactive labels, the Label Free Intrinsic Imaging (LFII) paradigm we pioneered. We have successfully achieved the capability of sequencing DNA up to many hundreds of base pairs, with no labels, at rates approximately 1000 times that of the conventional technology. We recently made the world’s first separation of different glycoforms of protein in a real-time label-free system. Our LFII system has been adopted by a major pharmaceutical company. Our high throughput analysis systems won the Platinum (Top) Prize in the IEEE ‘Supercomputing 2002’ conference in Baltimore.

**Grid Computing Projects**

D. I. Britton, D. J. Colling, P. Lewis, B. MacEvoy, J. A. Nash and R. Walker

The current and future generation of High Energy Physics experiments will produce massive amounts of data that will far outstrip the capability of existing computing to store and process them. In order to resolve the situation R&D is taking place into greatly improving distributed computer processing employing "Grid" technologies. The Grid is an innovative system for connecting computers around the globe, allowing them to share the work of storing and processing information. Work on prototype Grid projects is underway in many centres in Europe and the US; we have a team of people investigating several aspects of Grid computing including Grid scheduling and job control. In this work we collaborate closely with the Department of Computing and the London e-Science Centre.
The Blackett Laboratory Laser Consortium is carrying out research that explores the new frontiers of science made possible by high power ultra-short laser pulses. This exciting area of science includes controlling molecular and chemical processes, generating attosecond duration light pulses, producing coherent radiation in the X-ray region and creating high energy density plasmas. We operate two high power lasers, a sub-picosecond glass system delivering over a joule per pulse, and a 50 fs titanium:sapphire system delivering 100 mJ pulses. Using these lasers and through our accompanying theoretical work we are making pioneering contributions to the fields of ultra-short pulse generation, non-linear optics, plasma physics, and molecular dynamics. We are funded by a £1.4M programme grant from EPSRC/MOD and have received substantial additional funding from both the EPSRC and the European Union (COCOMO Research Training Network). We are engaged in a number of international collaborations with groups in Europe and North America. The Blackett Laboratory Laser Consortium forms part of the Quantum Optics and Laser Science Group.

A large programme on Attosecond Technology – Light Sources, Metrology and Applications supported by the Basic Technology Programme of the UK Research Councils has just been announced. We will be the centre of this £3.5M national programme, collaborating with Kings College London, Rutherford Appleton Laboratory, and the Universities of Oxford, Reading, Newcastle and Birmingham. The attosecond system will be located within our laboratories following the completion of the current SRIF funded building up-grade.

A theoretical problem on which we have recently been active is high order harmonic generation (HHG) and more generally the dynamics of strongly driven electrons in molecular systems. This has contributed to a better understanding of our earlier experiments on high order harmonic emission in molecules. Theoretical investigations of these effects in H$_2^+$ and H$_2$ molecules have enabled us to establish a picture for this process and to quantify the role of dipole phase and amplitude in random and aligned ensembles of molecules. A numerical integration of the Schrödinger equation was performed for the electron in a suitable two centre potential exposed to a short intense laser field. A quantum interference effect in the electron wavefunction is seen to suppress emission of certain harmonic orders at a critical angle. Essentially, contributions to the harmonic emission from the driven electronic dipole are cancelled due to the existence of contributions of equal magnitude but opposite sign emitted by the two atomic centres of the molecule.

The interference we have identified is general in nature and should apply to all molecules. Moreover it also applies to the electron re-scattering from the molecule. Our most recent calculations have verified that for sufficiently high energy re-scattered electrons the interference between the two scattering centres leads to constructive and destructive interference of the scattered wave as a function of scattering angle. In Figure 1 the angle dependent scattering of electrons at an energy of 250 eV from a H$_2^+$ molecule are shown for two different inter-nuclear separations (2.5 x 10^{-10}m and 5x 10^{-10}m). The fringe spacing in the interference pattern can be directly related to the inter-nuclear distance in these two cases. This is an example of electron diffraction, but in a unique regime where the electrons are derived internally from the molecule itself by the strong field. In principle this could provide structural information on the molecule on a sub-Angstrom distance scale with sub-femtosecond temporal resolution.

In collaboration with the NRC in Canada we are carrying out calculations of the modified multi-photon ionisation that can occur in a dielectric medium in a strong field. This has implications for new techniques of creating microscopic optical structures by laser induced modifications of glasses.

Work has been completed on the installation of an all reflective, broad band, spatial light modulator (SLM) into our Ti:Sapphire femtosecond laser system.

\[ R = 5 \text{ a.u.} \]

\[ R = 10 \text{ a.u.} \]

**Figure 1. Angular distribution of scattered electrons**
laser system. The SLM is a very powerful tool that allows us to create arbitrarily shaped laser pulses through control of the delay of individual frequency components of the laser beam. A diffraction grating and cylindrical mirror separate and collimate the different frequency components of the laser beam onto a liquid crystal phase mask made up of 640 pixels. The beam is then spectrally recombined using an identical cylindrical mirror and diffraction grating. Each pixel can be controlled individually and delays the light passing through it by an amount proportional to the applied voltage, allowing fine control over the shape of the laser pulse. Current work includes the development of a genetic algorithm to control the light modulator via feedback from an experiment that will generate pulse shapes that optimise a specific outcome of the experiment.

A Frequency Resolved Optical Gating (FROG) diagnostic based upon polarization gating was also constructed and installed this year. This gives us the capability to fully analyze the optical phase and amplitude for laser pulses at around 800 nm with a pulse duration between 3 ps and 30 fs.

Figure 2. Multiple-order Raman spectra excited by a pair of ~100 fs pulses.

800 nm beam and OPG (650 nm) through fiber filled with CH4

Counts (a.u.)

Wavelength (nm)


Non-linear Optics in Intense Laser Fields

A major activity in the last year has been to explore ways to produce sub-femtosecond intense laser pulses. One promising technique is based upon stimulated Raman scattering from strongly driven molecular vibrations. We have employed two short laser pulses tuned to Raman resonance to greatly increase the efficiency of side-band generation compared to the case when a single frequency is applied. The laser fundamental at 800 nm and the tunable output of an Optical Parametric Generator (OPG) are tuned into Raman resonance with the main vibrational modes of the chosen molecule. The OPG is driven by the second harmonic of the fundamental and seeded by white light derived by focusing a small portion of the fundamental into a CaF crystal. An energy per pulse of up to 1 mJ has been obtained in the resulting tunable output. We focus both the remaining fundamental and the output of the OPG (typically ~100 μJ in each) into a hollow core fibre containing the molecular sample at a density of ~500 mbar. Both H2 and CH4 were studied. Both showed greatly enhanced side-band generation if the pair of Raman resonant pulses were introduced compared to the case of a pump alone (see Figure 2). Work using adiabatic techniques to drive high vibrational coherence is also reported elsewhere (see QOLS group section).

The anisotropy of molecules plays a significant role in HHG. We previously highlighted the role of molecular alignment upon HHG. We produced alignment in molecular samples (e.g. CS2) using the electric field of a 300 ps duration laser pulse derived from the stretched pulse of our Ti:sapphire laser. The alignment technique allows us to modulate and enhance HHG produced by the recompressed (70 fs), high intensity (10^{15} W cm^{-2}) pulse. We believe that the enhancement arises from the better control in aligned molecular ensembles of the phase of the non-linear polarisation responsible for harmonic emission. Further experiments in the past year on a variety of molecules including CS2 and CO2 as well as various atoms have contributed to an improved understanding of the complex interactions that occur when molecules are exposed to intense laser fields.

K. Mendham, N. Hay, J. W. G. Tisch, R. A. Smith and J. P. Marangos

Cluster Heating Studies

Our previous research has shown that clusters of atoms comprising more than about 1000 atoms can be very efficiently heated with intense (>10^{15} Wcm^{-2}) femtosecond laser pulses. The heated clusters explode to produce electrons with energies in the keV range and highly charged ions extending out to 1 MeV. When a laser-irradiated deuterium cluster explodes, the kinetic energies of the deuterons are even sufficient to drive nuclear fusion, providing a short-pulse (ps) source of neutrons. Also, the plasma that is formed when a high density cluster medium is laser-
heated becomes a very bright emitter of x-rays in the keV range, producing very little debris. Owing to these applications, interest in this field continues to grow.

The recent focus of our research has been to see whether the heating of a cluster can be made even more efficient by changing the shape of the laser pulse, since it is known that the dynamics of the interaction are sensitive to the time-dependent laser field the cluster "sees". We are currently installing a pulse shaper into our high power Ti:sapphire laser system that will allow us to control the pulse phase and amplitude, permitting us to synthesise almost any pulse shape. Ahead of this development, we have been experimenting with laser pulses that have small (<10% of the main pulse intensity) pre- or postpulses, which we can generate easily within the existing laser system as a stepping-stone to more sophisticated pulse shaping. We were also able to change the duration of the main pulse. We found that the ion energies from exploding Xe, Kr and Ar clusters (of about 5 nm in radius) differed by up to a factor of 2 depending on whether a prepulse or postpulse was used (see Figure 3). Compared to a pulse without pre or postpulses, the increase in ion energy is more than a factor of 2.

Detailed simulations of the laser-cluster interaction show that the presence of a pre or postpulse changes the timing of a resonance in the cluster heating that is known to be responsible for the high ion energies observed. Essentially, when the resonance is shifted closer to the peak of the laser pulse, the ion energies are increased. Whether this is achieved with a pre or post-pulse depends on the atomic species, cluster size and main pulse duration. These results suggest that much bigger increases can be achieved using the aforementioned shaper to make more complex pulse shapes.

**Plasmas formed from Cluster and Microdroplet Media**

D. Symes, A. Moore, J. W. G. Tisch and R. A. Smith

Microscopic objects such as atomic clusters containing a few thousand atoms are extremely fragile and easily destroyed by raising their temperature several tens of Kelvin. Despite this, they provide a unique and very effective way of producing high energy density plasmas in the laboratory. In an intense, sub-picosecond laser field clusters are ionised and expand on a timescale of a hundred femtoseconds. During this expansion they undergo a transient plasma resonance and large amounts of energy can be transferred to the cluster. Individual clusters then explode and produce an extended plasma with a mean temperature of several KeV. We have used the fragility of atomic clusters, together with their ability to absorb intense laser light to carry out a new series of experiments on modulated blast-waves. By destroying clusters in selected regions of an extended medium with a low power laser we can tailor the energy deposited by a high power pulse. Figure 4 shows a modulated blast wave produced in this way, and imaged with a sub-picosecond optical probe. These modulated blast-waves can be used to investigate how expanding supernova interact with the cold interstellar medium.

The interaction of short, intense laser pulses with micron-diameter liquid droplets has been further investigated by using ion spectroscopy, supported by detailed numerical modelling. Ion yields from single droplets irradiated by 100 fs laser pulses focussed to intensities of $10^{16}$ and $10^{17}$ Wcm$^{-2}$ are shown in Figure 5. The closeness of the target diameter to the laser wavelength produces electric field hot-spots across the droplet surface which drive non-uniform heating. The droplet surface undergoes a highly anisotropic, polarisation dependent explosion, generating energetic multi-keV ions and causing a compression of warm core material. The subsequent core expansion does not depend on the laser polarisation, since the temperature throughout the target has equilibrated by this point in time. The surprisingly non-spherical character of the droplet explosion found in experiments can be explained by modelling the non-radial pressure gradients which deform the target during compression. The acceleration of ions to high energies we have observed also indicates the future potential of microdroplets as a source for applications such as proton radiography, isotope production and short-pulse neutron generation.
The broad themes of our research are: adaptive optics applied to astronomy and medical imaging; biomedical optics and photonics, including high-speed 3-D imaging and fluorescence lifetime imaging; electromagnetic theory, particularly of chiral media, Bragg structures and negative index media; high power fibre laser technology, including telecommunications amplifiers and sources, nonlinear fibre optics and compact high power visible/UV sources; optical fibre sensors, high power solid-state laser technology and nonlinear optics; ultrafast diode-pumped solid-state and fibre laser technology and optical storage.

**Optical Fibre Laser Technology**

S. Popov and J. R. Taylor

With the continuing downturn in the optical telecommunications market, the emphasis placed on the research programmes undertaken throughout 2002 has reflected our belief that optical fibre based devices will play major roles in important fields outside telecommunications. As a consequence, our research on basic broad-band amplifiers, specifically that on fibre Raman devices, has been drastically reduced.

Our development of MOPFA (Master Oscillator Power Fibre Amplifier) technology has continued to focus on versatile compact seed sources that are deployed with high power, fibre-based amplifiers (Yb, Yb:Er and Raman) to generate high average power sources with versatile wavelength and pulse format. These sources are particularly applicable to non-linear optical conversion allowing extended wavelength coverage. A particular highlight of the year has been the demonstration of multi-watt level, compact, red-green-blue sources based upon frequency doubling and mixing of Yb and Yb:Er based MOPFA systems in periodically poled non-linear materials and extension of the converted wavelength ranges to the deep UV.

Although basic research on Raman amplifier configurations has ceased, they have been extensively deployed in simple pulse length- and repetition rate-tunable femtosecond/ picosecond pulse sources exploiting adiabatic amplification of optical solitons. We have also developed a new optical time domain reflectometry technique for measurement of gain in distributed and lumped Raman amplifiers. We have also characterised the Raman gain of "holey fibres" and found that devices based on conventional fibre typically offer higher performance.

One area where "holey fibre" has a unique characteristic is in the ability through modification of the waveguide to tailor the zero dispersion wavelengths to the visible wavelength range. Consequently, anomalous dispersion leading to soliton-like pulse shaping is now possible in the visible range in all-fibre format. We have demonstrated thus the first all-fibre femtosecond Yb doped "figure of eight" laser. Various other novel configurations for all fibre femtosecond generation in the visible and near infra red are currently under investigation. Holey fibre has also allowed up to 5W, high power broad-band continua to be produced pumped by MOPFA configurations in all-fibre formats.

**Nonlinear Optics and Laser Technology**

M. J. Damzen

A key problem to scaling the power of solid-state lasers is strong heating effects in the laser amplifier leading to thermally-induced lensing and stress-induced birefringence that degrade beam quality and reduce stability and efficiency of the laser. We have developed a range of nonlinear techniques to provide self-organised correction of many of these adverse effects, pioneering radically new self-adaptive solid-state laser systems that maintain the laser efficiency and output beam quality by exploiting a novel dynamic holography process within the laser amplifier itself. Building on our earlier work using pulsed lamp and laser pumped systems, we have demonstrated continuous-wave diode-pumped solid-state laser with adaptive resonator operating at many tens of watts with diffraction-limited beam quality. Currently we are developing adaptive interferometers for a range of real-world applications including remote ultrasound detection for non-destructive testing, medical biomechanical health and free-space optical communications. A programme to characterise new nonlinear optical media complements the work on nonlinear optics. As well as including the conventional bulk nonlinear crystal media such as KTP, we have work extensively with photorefractive media that have strong nonlinear effects even at low light levels ~ 1 mW.

We are developing novel high power solid-state laser devices for a range of applications ranging from industrial processing to medicine, laser displays and information technology. Our novel side-pumped designs operate at high output power levels (10-100 W) with record conversion efficiencies (60%-70%) for bulk solid-state lasers. These sources are expected to have immediate impact for industrial material processing applications. By using different laser media and different transitions with nonlinear frequency conversion, we are developing new compact efficient sources at high average power (multi-watt) in the red, green, blue and UV spectral
regions for application including medicine and laser displays.

We are currently initiating a new nanotechnology programme to study nonlinear optical properties of carbon nanotubes and biological microtubules for new materials for information processing and sensors Figure 1.

Sculptured Thin Films

M. W. McCall

Sculptured Thin Films are formed by vacuum deposition of vaporised material onto a substrate that moves in a periodic fashion during growth. For a rotating substrate a chiral morphology results in which the material forms into helicoidal columns (Figure 2). Chiral sculptured thin films have some promise for various sensing and filtering operations, as their properties are selective to circularly polarised light. Our recent research has shown how chiral mirrors can be used to design a circularly polarised resonator (see Figure 3).

Figure 2. Scanning electron micrograph of a chiral sculptured thin film (courtesy of Pennsylvania State University).

This optical data storage work makes use of our research developing numerical methods, such as Finite Element (FE) and Finite Difference Time Domain (FDTD) for analytical models of optical systems including the notoriously difficult high aperture optical systems. Fully analytical models may only be constructed when the specimen is much smaller than the wavelength or it has special properties, such as full rotational symmetry. The interaction of tightly focused light with complicated specimen structures must be computed by means of numerical methods. Our research aims at incorporating analytical and numerical models to reliably predict imaging properties of optical systems and it permits the description of partially coherent high aperture systems. Our models also include polarisation effects and we are developing a method to produce an arbitrary polarisation structure in the vicinity of focus of high NA lenses. We take a combination of vectorial Gauss-Laguerre and Gauss-Hermite beams as basis functions that we use to expand a 'wish function' describing the polarisation structure in question. This research has great use in optical data storage, ellipsometry and polarised light optical microscopy.

High Resolution Imaging of the Human Retina using Adaptive Optics

D. P. Catlin, J. C. Dainty, I. Munro, C. Patterson and F. C. Reavell

The human eye has significant optical defects that distorts an optical wavefront passing through it blurring the retinal image. In order to obtain high resolution retinal images that allow individual photoreceptors, approximately 2 μm in diameter, to be observed requires the wavefront aberrations of the eye to be accurately measured and corrected for across a wide, dilated pupil. The wavefront aberrations of the human eye are recorded by using a Shack-Hartmann wavefront sensor, which consists of a compact tightly grouped array of lenslets. The device is located in the light path in such a way that each tiny lenslet forms an image of the retina on the surface of a CCD. If the light wave is perfectly flat then each lenslet produces an image spot located at the focal point of each lenslet. However if the light wave is not perfectly flat then the images produced by the lenslet array are shifted from their central positions. Measuring the displacement of each spot provides a snapshot of the light beam's aberration. Once the slope measurements are known the wavefront aberration is reconstructed using a series of Zernike polynomials. Imaging is achieved by using a Fourier deconvolution technique. The method uses multiple wavefront aberration data and multiple degraded images to provide an ensemble
maximum likelihood estimate of the undistorted object. In this way we aim to produce high quality in vivo images of the human retina that will provide new opportunities for studying vision and for clinical diagnosis.

P. M. W. French, I. Munro, M. Neil and F. C. Reavell

Throughout 2002, we have continued to develop ultrafast laser based technology for novel imaging applications with a strong emphasis on biomedical imaging and microscopy. Our philosophy is to develop new imaging technology for both clinical and interdisciplinary research applications that can exploit state-of-the-art and future anticipated ultrafast and tunable laser technology including compact diode-pumped all-solid-state and fibre laser sources.

Currently we are focusing on two main areas: 3-D imaging using coherence gated imaging and fluorescence lifetime imaging (FLIM). The former programme builds on our invention and development of time-gated imaging using low coherence photorefractive holography to provide a unique 2-D and depth-resolved 3-D imaging modality, applicable through scattering media, that offers an inherent rejection of a dc (diffuse light) background. The use of photorefractive GaAs/AlGaAs MQW devices, in partnership with David Nolte at Purdue University, has realized wide-field depth resolved imaging at ~500 frames/second.

We have also investigated other techniques for wide-field optical sectioning including low coherence interferometric imaging with direct CCD detection and structured illumination. Potential biomedical applications include a safe, low-cost, non-invasive optical biopsy tool to study and screen for skin cancer and other diseases. These techniques are also generally applicable for 3-D microscopy of dynamic (living) subjects and on a macroscopic scale may be used to image large (including remote) 3-D objects, e.g. for facsimile transmission or input into 3-D graphics software. Our fluorescence lifetime imaging (FLIM) programme also concentrates on wide-field image acquisition, offering sub-10 ps temporal discrimination for wide-field functional imaging of chemical and biological samples, contrasting different chemical species and different fluorophore environments.

We have worked to combine FLIM with multi-spectral imaging and optical sectioning to realize 5D fluorescence imaging and have adapted FLIM to polarization anisotropy to image rotational diffusion dynamics. Our novel FLIM instrumentation is complemented by a confocal scanning/multiphoton microscope and broadly tunable ultrafast laser technology to provide a unique opportunity for functional biomedical imaging. This resource is being developed for collaborative projects with the Bioengineering, Biology, Chemistry Departments and the Faculty of Medicine. In molecular biology FLIM is used with genetically expressed probes such as EGFP, to report not only the localization of the specific protein to which the EGFP is tagged, but also the local fluorophore (protein) environment. For medical applications FLIM provides intrinsic contrast from autofluorescence of unstained tissue samples, as shown in Figure 5, with potential applications to non-invasive diagnosis of disease and to in situ quantitative monitoring of tissue during therapeutic intervention. We have recently received a DTI Beacon Award and a Wellcome Trust Showcase Award to develop FLIM and related technologies for biological research, clinical evaluation and high-throughput assay technology.
Plasma Physics

Head of Group:
Professor S. C. Cowley

The Plasma Physics group studies ionized gases and their interaction with electromagnetic fields in the laboratory and the universe. A large part of the Group’s effort is directed towards the physics of schemes for generating fusion power. We perform theoretical, experimental and computational research in all areas of fusion research. High powered lasers and pulsed power devices (such as MAGPIE in the basement of the department) have produced novel high energy density states of matter that we are exploring. For example, using lasers we have studied gigantic magnetic fields (340 Mega-gauss) and relativistic plasmas. With MAGPIE we have made jets that scale appropriately to astrophysical jets. Theoretical studies of astrophysical plasmas focus on the origin of magnetic fields and cosmic rays.

Magnetic Fusion Research


In collaboration with Culham laboratory and at the Joint European Torus (JET) the Group is investigating the physics of magnetic fusion. This field is preparing to build an internationally funded experiment (ITER) that will, for the first time, ignite a plasma with fusion reactions. Although we are deeply involved in the central issues this device will face, primarily turbulence and explosive instability, we are also investigating various concepts to improve fusion plasma efficiency.

Figure 1. Explosive finger of plasma carrying a magnetic field line out of a fusion plasma from theoretical model.

Fusion plasmas confined by magnetic fields are plagued by turbulence and instabilities. We have developed computational techniques and codes to simulate the turbulence. Recently quiescent states that greatly enhance the fusion performance have been discovered in experiments on JET. Our simulations have shown how these states are created by turbulence driven sheared plasma flows. They have also shown that specific magnetic field configurations enhance the generation of these turbulence free states. Further work in this area to understand these states and how to access them in ITER and other future devices is under way.

One of the issues facing all magnetic fusion concepts is the explosive loss of plasma and the damage it causes to the devices. We are measuring this loss and the impact on the walls of the device. A new theoretical model has been developed to explain the explosive loss of plasma. In Figure 1 we show the theoretically predicted finger of plasma that explodes to the wall. The model predicts that the explosive loss may be made tolerable by shaping the plasma into a triangular shape.

Ultra-high magnetic field measurements

K. Krushelnick, A. E. Dangor, M. Tatarakis, A. Gopal, F. N. Beg and M. S. Wei

Very large magnetic fields (up to 1 GigaGauss) have been predicted by computer simulations and analytical calculations to exist in the high density region of the plasmas produced during high intensity laser-matter interactions. In the past, the principal diagnostic for magnetic field measurements in laser produced plasmas has been Faraday rotation of transversely propagating external probe beams. However, because of refraction effects only magnetic fields in the outer coronal plasma can be observed using this technique. These fields are up to 5 MGauss, which is far lower than the strength of the predicted magnetic fields generated at or near the critical surface. However, we have made measurements of the self generated magnetic field during an ultra-high intensity (>10^{19} Wcm^{-2}) shot pulse (0.7 - 1 ps) laser-plasma interaction experiment using an innovative method. We have shown that polarisation measurements of self-generated harmonics of the laser can provide a convenient method for diagnosing the magnetic field in these interactions - and that our experimental measurements indicate the existence of fields in excess of 340 MegaGauss. These observations are important for evaluating the use of intense lasers in various potential applications and perhaps for understanding the complex physics of exotic astrophysical objects such as neutron stars.

Fast Ignition Experiments


One way of reducing the criteria for ignition in Inertial Confinement Fusion experiments is the so-called "fast ignition concept" – in which the interaction of an ultra-intense laser pulse with a dense plasma generates a high current electron beam capable of heating and igniting a compressed fusion pellet. One of the difficulties with this scheme is the propagation of a high intensity laser pulse through the long distance of low density plasma which usually surrounds the compressed core. However, we have been working on a way of avoiding this problem through the use of conical implosions – which provides a clear path for the high intensity pulse (see Figure 2). At the Institute of Laser Engineering at Osaka University in Japan we have been involved in experiments in which all of the components for the Fast Ignition scheme have been tested simultaneously for the first time. In these experiments, we have found that, by using this conical compression geometry, a compressed pellet can be heated significantly by the hot electrons created by the intense laser beam.
Wire array Z-pinch implosions

S. V. Lebedev, J. P. Chittenden, S. N. Bland, D. J. Ampleford, C. A. Jennings, M. Sherlock, and M. G. Haines

One approach to achieving controlled thermonuclear fusion in the laboratory is to use X-rays from an imploding Z-pinch plasma to energise an X-ray cavity surrounding a capsule of deuterium and tritium. Achieving external control over the shape of the X-ray power pulse is an important requirement for future Z-pinch driven fusion ignition experiments. We are currently exploring the use of two concentric (or nested) arrays of fine metallic wires for pulse shaping on our 1.5 MA MAGPIE pulsed power facility. The shape of the TW X-ray pulse is controlled by the dynamics of the “snowplough” phase of the outer array implosion, and by the delay between the stagnation of the outer and the inner arrays (Figure 3).

Figure 3. Implosion trajectories and X-ray pulses from the single and nested wire array z-pinches.

Using our 3D resistive magneto-hydrodynamics simulation, we have been studying the generation of X-rays during implosion phase of wire array Z-pinches. Non-uniform ablation of the wires results in a strong modulation of the plasma flow injected into the interior of the array and later on causes a break-up of the imploding plasma. This limits the ability of the driving current to follow the implosion down to the axis, which in turn controls the kinetic and Ohmic heat sources in the imploded plasma and hence the X-ray power emitted.

Laser produced plasmas as a compact particle accelerator


High intensity laser produced plasmas are capable of accelerating particles to high energies over very short distances. We have been exploring these interactions for this application as well as examining the fundamental physics of the propagation of ultra-high intensity laser pulses through gaseous density plasmas.

Recently we have measured plasma electrons accelerated to energies in excess of 200 MeV in a distance of only 1 mm. This electron energy spectrum was obtained using the high intensity laser at the LOA facility near Paris, which can be focused to intensities greater than $10^{19}$ W/cm$^2$ in a 30 fs pulse. Particle-in-cell simulations performed on our home-built computer clusters, as well as in 3D on supercomputers, have shown that the electrons are generated in a complex interaction of non-linear processes. This interaction severely modifies the laser pulse (creating a sharp rising edge), which generates the required accelerating structure. This mechanism has been called a forced laser wakefield.

Generating an axial magnetic field from photon spin

M. G. Haines

Photons have spin $\hbar$ and in circularly polarised light these spins are aligned, and lead to angular momentum in the beam. When a circularly polarised laser beam is absorbed by a plasma, the angular momentum is deposited in the electrons at first, exerting a torque which drives an azimuthal current. For a pulsed laser an azimuthal electric field is induced to oppose the torque on the electrons. It then follows from Faraday’s Law that an axial magnetic field will be generated. Estimates for the magnitude of this axial magnetic field for photon spin are in reasonable agreement with the 7 MG fields recently determined experimentally by the Group.

Figure 2. Upper figure: gold conical insert and deuterated plastic shell before implosion. Lower figure: Image of x-ray emission from implosion showing that compression is relatively uniform.

Figure 4. Electron spectra $n_e = 2.5 \times 10^{19}$ cm$^{-3}$ (squares) and for $n_e = 6 \times 10^{19}$ cm$^{-3}$ (circles), showing extension of the spectrum to $> 200$ MeV at the lower density.
The experiments are presently being scaled up to the recently commissioned Petawatt laser at the Rutherford-Appleton Laboratory, which can be focused to intensities in excess of $10^{20}$ W/cm$^2$.

**Laser-plasma transport modelling**

R. J. Kingham, A. Robinson and M.G. Haines

Recent experiments involving the interaction of a ultra-high intensity, sub-picosecond laser pulse with thin solid targets have demonstrated the generation of beams of electrons and ions with relativistic energies plus intense magnetic fields of 100's of MG (see Figure 5.) There are still many open questions including how the beams form and propagate through the target.

We have developed a new kinetic code, KALOS, that can model the transport of relativistic beams of electrons through a dense, cold, background plasma and the associated production of strong magnetic fields in 2-D. KALOS solves the Fokker-Planck equation and Maxwell's equations to correctly describe the WHOLE range of electron collisionality. KALOS has been used to understand how the laser energised electrons resistively collimate into beams (due to self generated magnetic fields) as they propagate through the target. In turns out that beam formation is effective even if the fast electron source is not strongly anisotropic and that the time-scale for beam formation is 0.5-1 ps for current experimental conditions.

We have also continued to address thermal transport and magnetic field generation in the plasma ablated from the solid (see Figure 5).

**Laboratory experiments to simulate astrophysical jets**

S. V. Lebedev, J. P. Chittenden, A Ciardi, D. J. Ampleford, S. N. Bland, M. Sherlock, and M. G. Haines

The emerging field of laboratory astrophysics allows the non-linear evolution of dynamical astrophysical plasmas to be studied in a series of directly scaled laboratory experiments. One example is the use of the conical wire arrays on MAGPIE, which result in the formation of radiatively cooled plasma jets, that reproduce the behaviour of proto-stellar jets on the 0.1 parsec scale. The interaction of the jet with target plasmas formed from X-ray irradiation of plastic foils provides a scaled study of the propagation of proto-stellar jets through the inter-stellar medium (Figure 6).

**Turbulent magnetic fields in astrophysical plasmas**

S. C. Cowley, G. G. Howes, and A. A. Schekochihin

Astrophysical objects such as stars, accretion discs, galaxies and galaxy clusters all possess magnetic fields. These fields are believed to be generated and maintained in their present state by turbulent motions of the constituent plasmas. There are two kinds of fields: small-scale fluctuations and large-scale structured fields.

Massively parallel supercomputers are being used to simulate the turbulent dynamo - the process of magnetic-energy amplification from tiny seed fields to dynamically important levels - and the ensuing nonlinear self-consistent turbulent states. Using modern particle codes, we are also studying the large-scale dynamics of astrophysical discs and the emergence of structured magnetic fields.

**Figure 5.** Schematic of transport and magnetic field generation in laser-solid interactions.

**Figure 6.** Soft x-ray image of the laboratory jet interacting with plasma cloud.

**Figure 7.** Small-scale field structures in a simulation of MHD turbulence: magnetic-field strength in a cross-section of the simulation box.
Research in the QOLS Group encompasses a wide range of theoretical and experimental projects in quantum optics, quantum information processing, laser physics, and nonlinear optics. Our work on high-intensity light-matter interactions is described in the Laser Consortium entry (pages 19-21). Highlights of 2002 were the arrival of the cold atom physics group of Professor Ed Hinds and Dr Ben Sauer from the University of Sussex, and the return of Dr John Tisch to a Lectureship.

**IonTraps and Laser Cooling**

**R. C. Thompson D. M. Segal and S. de Echaniz**

Ion traps make possible many new types of experiment in fundamental physics and quantum optics. Our work falls into three categories: the dynamics of ions in traps; the use of laser-cooled trapped ions as a tool in quantum optics experiments; and the study of highly-charged atomic ions in the Penning trap.

![Figure 1. Image of a single magnesium ion obtained using the "axialisation" technique developed in our laboratory.](image)

Ion traps consist of electrodes that generate EM fields to trap ions for long periods of time. Our experiments generally start with the application of laser cooling to reduce the ion temperature to  <1K. The ions are then still not truly at rest, but oscillate at characteristic frequencies, which we measure from the arrival times of detected photons. We are also interested in sympathetic cooling, in which the temperature of molecular ions is reduced through long-range Coulomb collisions with laser-cooled atomic ions held in the same trap. This might produce a new way of preparing a sample of ultra-cold molecular ions.

An exciting new area of experimental quantum optics relates to quantum information processing, the ultimate goal being the realisation of a quantum computer. Our particular aim is to study decoherence processes. We have recently achieved the first laser cooling of Ca ions in a Penning trap, and we are currently working towards cooling a single calcium ion. We have developed an improved technique for laser cooling in the Penning trap, in which an additional external driving voltage is applied to the electrodes.

We take part in an EU research network (HITRAP) concerned with the study of highly charged ions in traps. We are developing novel spectroscopic techniques for probing the nuclear and atomic properties of these ions. We have a collaboration with the Wavelength Standards group at NPL, where the modified spontaneous emission of a single ion, mediated by the presence of a high-Q optical cavity is being studied.

**Quantum Optics and Quantum Computation**


The Quantum Optics and Quantum Information theory group is one of the largest of its kind in the world. Our work centres on understanding how quantum coherence can be created, manipulated and exploited in dissipative environments that tend to destroy quantum resources through decoherence processes. If we can understand how to manipulate quantum coherence, we will be able to construct addressable quantum registers, an essential building block of any future quantum computer. Underlying this is a long-term research programme concerned with the foundations of quantum theory, the nature of entanglement, non-locality, algorithmic complexity and the dynamics of open systems.

We have been very active in studying potential realisations of quantum gates. Candidates include laser-cooled trapped ions, atoms trapped in optical lattices, cavity quantum electrodynamics, guided atoms on "atomic chips", and solid-state excitations. To do so we use different mechanisms to control a system inside a non-trivial decoherence -free subspace. Other applications that require good control over the time evolution of open quantum systems are reliable single photon sources relevant to quantum cryptography.

Alternatively, geometric and topological time evolutions can be used for the implementation of quantum computation with a great robustness against errors. It has recently been realised that elementary gates in quantum computation can be implemented using only geometrical (as opposed to dynamical) phases. This approach has certain inbuilt fault tolerant features, such as resistance to some errors arising from the random interaction of the quantum computer with its environment. One of the more promising physical realisations would be in quantum dots.

Imagine that you flip a coin and look to see if you get a head or tail; the outcome is probabilistic. This basic element of classical randomness has a fascinating quantum counterpart. A quantum coin can, of course, be in a superposition of heads and tails, and if it is used to determine the path of a quantum particle in a random walk on a lattice, the particle is in a superposition of locations. With a suitable definition of average probability distribution for this "smeared out" quantum particle, it turns out that the distance it walks grows linearly with time (or number of tosses) rather than the classical dependence on the
account the fact that the environment interacts in an uncontrollable way with the system and apparatus, and reduces the efficiency of the measurement. It turns out that this situation is more complicated than in Everett’s analysis and that both the entanglement and classical correlations then become relevant. We have been investigating this kind of imperfect measurement and the development of correlations and entanglement between various subsystems involved in the measurement process.

Quantum communication schemes that employ the superposition principle and quantum entanglement are major applications in quantum information science. Indeed, a polarisation based cryptography scheme has already been demonstrated experimentally over distances of many kilometres. However, the manipulation of polarisation degrees of freedom is difficult when one aims at collective operations between photons (e.g. as required for quantum repeaters). We have been exploring a different route in which the continuous degrees of freedom of the light field modes are used rather than the polarization degrees of freedom. This promising approach offers a number of advantages concerning their experimental feasibility compared to other quantum systems. We are studying systematically the capabilities of such an approach with present technology.

We continued to study the properties of unstable resonator modes with emphasis on fractal properties. We undertook an in-depth study of the Virtual Source method for generating one-dimensional modes, and applied the power method with translation to extend the Fox-Li method to the two-dimensional case.

We developed sophisticated computer codes for modelling optical parametric processes both in optical parametric chirped-pulse amplification (OPCPA) and in optical parametric oscillators (OPOs). We worked with Drs Ian Ross and Pavel Matousek at RAL on the detailed design of a three-stage OPCPA prototype experiment that will hopefully form the basis of a future major upgrade of the Vulcan laser. In the OPO work, we collaborated with Professor Wilson Sibbett and Dr Pablo Loza-Alvarez at St Andrews in the successful interpretation of OPO tuning characteristics.

We developed our understanding of femtosecond nonlinear optics beyond the slowly-varying envelope approximation and identified techniques for handling the situation where the spectra of different component fields overlap. We started to exploit the Finite-Difference Time Domain approach in this context, and this is likely to be a key focus of future work. We also made encouraging progress in the study of transverse effects in three-wave nonlinear interactions, especially in periodically-poled media.

We are using laser fields to create coherent superpositions of quantum states of atoms and molecules, which enable remarkable changes to be made to the optical and nonlinear optical properties of an ensemble of molecules or atoms. During 2002 our experimental

Entanglements are extra correlations between quantum systems over and above those allowed by classical physics. Although the process is well understood for two quantum systems, we still have very little understanding of entanglement for a large collection of systems. This is important because a quantum computer will involve a large number of qubits, and will therefore involve manipulating large entangled states. It is important to understand how the amount of entanglement is related to the potential speed-up in a quantum computer.

Figure 2. Comparison of the classical (dotted) and quantum (solid) probabilities of displacement x for walks on a line: note the dominant quantum interferences.
The combination of cluster beams with pulsed lasers opens up the subject of multiphoton excitation of metallic clusters, whose spectra are dominated by plasmon resonances. While the study of plasmons in single-photon and in collision experiments has been a notable feature of cluster physics, most of the strong laser field experiments (including those at Imperial College London) have involved the fragmentation or explosion of clusters. What we consider here is few-photon excitation of plasmons without destruction of the cluster. We have shown that two- three- and multi-photon excitations of plasmons in metallic clusters provide new information on their collective properties. Within current models, this type of information can be obtained theoretically, leading, it is hoped, to new experiments. This work is performed in collaboration with the Ioffe Institute in St Petersburg.

Our work on confined atoms has been pursued with the development of new models for the calculation of cavity resonances in metallofullerenes, and for their interactions with the atomic structure of the confined atoms. Confinement at the centre of a spherical fullerene cavity effectively isolates an atom from its environment, and this type of atoms exhibits properties of relevance to a number of situations in solid state and in surface chemistry. Indeed, confined atoms have even been proposed as a path towards the realisation of a solid-state quantum computer. Of particular interest in this connection is the behaviour of electron spin for the confined system. For a proper treatment of this, relativistic modelling is desirable. A fully relativistic extension of our work is in hand. The work is performed in collaboration with researchers in the USA, Russia, Thailand, and Uzbekistan.

We have continued to develop a detecting mirror system whose function is enhanced by the plasmon properties of the front reflecting surfaces, and a patent application has been filed, jointly between Imperial College London and the Shimadzu Research Laboratories (Europe) Ltd.
The Group carries out research in three closely related areas. The first is the physics of the Solar interior and atmosphere, including the ionised and magnetised outer atmosphere of the Sun. The second is the study of the extension of the solar atmosphere as the solar wind into interplanetary space, which forms the local environment of the planets of the solar system. The third is the physics of the Earth’s neutral atmosphere and the role it plays in the climate system, including the interactions between solar radiation and the atmosphere.

In the past year, we have continued to receive exciting new data from the four-spacecraft Cluster mission, allowing unprecedented insights into both large and small scale processes at work in the Earth’s magnetosphere. Our magnetometer onboard the Ulysses space probe has continued to make observations over the Sun’s poles, exploring quite unknown regions of the Solar System. In the far reaches of the Solar System, the Cassini spacecraft, which also carries a magnetometer produced by our Group, will reach Saturn in July 2004: it continues to observe the interplanetary medium as it travels. Having built the magnetometers for these spacecraft, and seen them sent deep into the Solar System, we are now exploiting the magnetic field observations made. In solar physics, observations have revealed interesting solar latitudinal variations in the properties of the sub-surface shear zone.

In the area of atmospheric and climate research we have continued to study the radiative properties of the Earth’s atmosphere and climate, exploiting data from Earth-orbiting satellites, and powerful theoretical models. We are the principal scientific team responsible for a new satellite radiometer, the Geostationary Earth Radiation Budget (GERB) experiment, which was successfully launched on the Meteosat Second Generation Satellite (MSG-1) in August 2002 and began sending back high quality images of the Earth in December 2002 (see cover).

GERB-3 has now been calibrated in our sophisticated Earth Observation Calibration Facility. During 2002 measurements of radiative fluxes in the far infrared red, in the upper trosphere have been made successfully by our TAFTS (Tropospheric Airborne Fourier Transform Spectrometer), during a campaign in Australia.

Analysis of solar energetic particle data from our Anisotropy Telescope particle detector on Ulysses have revealed large delays in particles reaching high heliographic latitudes. This finding challenges current models of energetic particle propagation, and suggests that cross field diffusion is more important than previously thought.

On the theory side, we are continuing to model interplanetary coronal mass ejections (CMEs). Our research has focussed on understanding how these structures interact with the solar wind, through both aerodynamic...
drag and magnetic reconnection. It indicates that in the right solar wind conditions, CMEs can survive to large distances in the solar wind.

**Planetary Plasma Physics**

M. K. Dougherty and A. Balogh

Our work in this area has concentrated on understanding the physical processes arising in the giant planet magnetospheres, that of Jupiter and Saturn. We are the Principal Investigator institute for the dual technique magnetometer onboard the NASA/ESA Cassini orbiter which will reach Saturn in July 2004 for the start of its four-year orbital tour. Part of our preparation for the Saturn magnetospheric observations to come consists of careful analysis of the previous data sets obtained by the Pioneer and Voyager flybys of Saturn. This has revealed that accurate modelling of the current sheet at Saturn requires taking account of temporal variations related to the condition of the magnetosphere (which is dependent on solar wind conditions), as well as non-axisymmetric contributions due to local time effects. This will be very important during Saturn Orbit Insertion and subsequent close approaches to the planet when we will resolve the higher order moments of the internal planetary field, thereby allowing us to gain an understanding of the interior of the planet itself.

The Cassini flyby of Jupiter in late 2000 whilst the Galileo spacecraft was in orbit around the planet resulted in a collection of Nature papers as a result of this unique dual spacecraft opportunity. This work clearly showed the influence of the solar wind on the workings of the magnetosphere of Jupiter and revealed the magnetosphere in a state of transition from an inflated to a much smaller state. In addition clear solar wind control of radio and auroral emissions were observed. A pulsating auroral X-ray hotspot on Jupiter was also observed during this period which seems to be driven by internal processes within the magnetosphere itself.

The Rosetta probe will perform the first ever in-depth study of a comet nucleus, and will observe the development of activity as the comet approaches the Sun. Our Group provided the data-processing unit for a suite of sensors to measure plasma properties and is one of the six Principal Investigator teams which comprise the Rosetta Plasma Consortium. These sensors will study the interaction of the comet’s tenuous mixed atmosphere of dust, gas and plasma, with the solar wind. Due to the launch postponement, ESA will soon target the mission towards a new comet.

**Solar Terrestrial Physics**

A. Balogh, P. Cargill and T. S. Horbury

Analysis of data from the Group’s magnetometers flying on the four Cluster spacecraft, launched in July and August 2000, continues to be a major activity.

Research has focussed on the three dimensional aspects of the structure of boundary layers in the magnetosphere and solar wind. The structure of the bow shock as been shown to be intrinsically three dimensional, with the range of scales that leads to plasma thermalisation being a considerably more complex process than had been previously believed. Using the "curlometer" technique, the electric currents associated with the bow shock have also been measured for the first time.

A recent study has examined hot flow anomalies (HFAs): explosive disturbances to the bow shock, caused by a change in the direction of the interplanetary magnetic field. Particles are energised and channelled along the discontinuity, causing a rapidly expanding bubble of hot plasma. Figure 3 is a sketch of an HFA encounter derived from Cluster magnetic field data, in collaboration with the plasma instrument team, showing the sizes and orientations of structures within the event.

Another focus has been on the magnetospheric polar cusps, regions that provide the easiest access of solar wind energy to the auroral regions. We have played a leading role in investigating these poorly understood regions of space, and have shown that they are highly dynamic, moving around apparently in response to changing interplanetary conditions, and have totally different structures when viewed in the plasma and magnetic field.

**Physics of the Earth’s Atmosphere**

J. D. Haigh, R. Toumi and J. E. Harries

This research programme is directed at understanding the physics of the Earth’s neutral atmosphere and the role it plays in the climate system. The general circulation, composition and energy balance of the atmosphere are determined by a combination of fluid dynamical, radiative and chemical factors. We can investigate this using observations (from satellites, airborne and ground-based instruments) and with theoretical models. We are particularly interested in how electromagnetic radiation is transferred by the atmosphere and how measurements of the Earth’s radiation field...
very important for separating natural atmospheric variability from that in the lower atmosphere. These sorts of studies are in the general circulation of the lower atmosphere. We have shown that the initial effect of both these phenomena eruptions. We have found a signal of the same magnitude, but in the opposite sense, as that due to stratospheric ozone decreases. We have also been looking at the formation of contrails by aircraft over Europe. Contrails are thought to have a warming effect on the climate and their formation probability is strongly affected by the ambient water vapour and temperature. We have quantified, using climate and aircraft simulation models, the effect of flying at lower altitudes to reduce contrails. CO$_2$ emission would increase but the effect of contrails could be removed, giving a net reduction in the warming effect of aircraft.

We have been using computer simulations to study the response of the atmosphere to increases in solar ultraviolet radiation and to large volcanic eruptions. We have shown that the initial effect of both these phenomena is to heat the lower stratosphere and that subsequently this causes a change in the general circulation of the lower atmosphere. These sorts of studies are very important for separating natural atmospheric variability from that imposed by human activity.

In collaboration with the Complex Systems Modelling Group (Department of Earth Sciences and Engineering) we have developed a new model for calculating 3D scattering of radiation within inhomogeneous cloud. In an atmospheric physics contest the model is unique and is now being used to study how cloud structure affects the Earth’s radiation budget.

**Earth Observation and Data Analysis**

_J. E. Harries, J. D. Haigh and R. Toumi_

Mountains are particularly vulnerable to changes in climate. Dramatic reductions of glaciers have been observed. Other changes in the mountain weather are highly uncertain due to a lack of data. We will be making measurements of atmospheric pressure on a mountain to give us information about the local and large scale flow and is also a direct measure of the average temperature below the mountain. The Himalaya (and Mt Everest) are of particular interest as observations there will allow us to study the upper air during the Indian Summer monsoon and the fast winds of the jet stream in Winter. Our barometer will give us the first high frequency (five minute resolution) data for this important region. Figure 5 shows the team after they placed our instrument on the South Col of Mt Everest at 8000 m.

Spectrally-resolved measurements of the infrared spectrum of energy escaping to space have shown, for the first time, direct evidence of a change in global greenhouse forcing. Further studies including cloudy skies indicate another exciting possibility: changes appear to account for a significant signal in the outgoing IR spectrum, though the signal is confused by sampling uncertainties. In related work, we have studied the time variability of the spectrally integrated outgoing longwave radiation (OLR). We are using wavelet analysis of time series of OLR data to examine for the first time the changes in quasi-periodic behaviour with time. We are also ‘slicing’ the OLR in different energy bands. This allows us to gain a measure of different cloud processes and how they vary in space and time. Specifically we are examining the El Nino-Southern Oscillation (ENSO), and the Madden-Julian Oscillations, of the tropical Pacific and Indian oceans. These results may provide further signals of how our climate is changing.

**Atmospheric Instrumentation Development - Space and Airborne Observations**

_J. E. Harries, R. Toumi and J. Pickering_

In the radiative energy balance of the Earth, a considerable fraction (20-35%) of the total cooling to space in the infrared derives from water vapour in the upper troposphere in the far infrared. We have developed the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS) to measure radiative fluxes at different levels in the troposphere, and to use these data to test climate models in this very sensitive part of the atmosphere. As part of the EMERALD 2 international collaboration to look at the radiation, micro-physical and dynamics of tropical cirrus cloud production from deep convection events, TAFTS was carried on flights from Darwin Australia during November 2002.

The Geostationary Earth Radiation Budget experiment (GERB) is designed to make highly accurate measurements of the reflected short-wave and emitted long-wave infrared radiation for the first time from geostationary orbit. We have calibrated the first three instruments (GERB-1, -2 and -3) in our Earth Observation Calibration Facility (EOCF) and are continuing to analyse the calibration results. The first GERB instrument is now in operation, and an analysis and assessment of the initial data are being made.
The recent evidence for neutrino oscillations is perhaps the most important particle physics discovery since that of the W⁺ and Z⁰. A problem with neutrino mixing is the construction of the unitarily inequivalent Hilbert spaces on which the corresponding field operators have to act. The original Pontecorvo formula is too naïve. We have calculated an oscillation formula in space, suitable for making direct connection with experiments, and which exhibits corrections to this formula.

More formally, the control of infinities in QFT is of central importance and an approach using zeta-function regularisation is central to most calculations in curved space-times. We have shown that zeta-function methods leave extra terms which make the extraction of physical predictions much more difficult, if not effectively impossible.

Current uses of field theory in the early universe and heavy-ion collisions require Thermal Field Theory - a description of systems at high temperature and density which may well be out of equilibrium. In such circumstances non-perturbative methods are obligatory, and our work implements these in a wide variety of applications.

As one important application, linear response theory is used to estimate transport coefficients in plasmas, but the resummations required to get results are very complex. Influenced by Luttinger liquids, where duality provides a natural resummation, we have used duality to calculate conductance in a hot relativistic plasma. As a further application of non-perturbative methods, the linear delta expansion has been successfully applied to the phase structure of scalar fields at finite density, a calculation not amenable to the usual lattice Monte-Carlo methods, and to the slow rollover problem which forms the basis of inflationary theories of the early universe.

In the context of slow-roll models, we have also examined the onset of classical behaviour, an a priori assumption in much of cosmology. The main result is that, in general, classical behaviour has taken over even before the transition is complete, and naïve stochastic classical analysis is valid. As a further ingredient in our understanding of classical behaviour, we have shown that the limiting procedure used by 't Hooft in obtaining truly quantum systems from deterministic ones amounts to a group contraction. We have proposed new deterministic models which map onto the quantum harmonic oscillator.

In parallel, we have begun to solve stochastic equations numerically, to look at the consequences of multiplicative noise, inevitable in non-equilibrium QFT. In a related activity, we have developed non-equilibrium methods for the dual worldlines that can be used to characterise transitions.

Stochastic classical equations are also used to describe non-equilibrium behaviour in condensed matter systems. A very fruitful approach is to ask the questions of condensed matter systems that we would of fields in the early universe and make predictions that can be confirmed by experiment. To this end we have proposed experiments with annular Josephson Junctions to test causal scaling bounds on the production of domains after phase transitions that mimic those of QFT. The first of these experiments, to measure topological defect densities, has been performed with remarkable success, and a second has been proposed.

Related research has addressed how topological defects can arise as classical objects from the basic quantum dynamics. The monopole mass can be shown to provide an order parameter in gauge theory. Extensive work has been done on solitons in SU(N) models. We found (N+1)/2 distinct classes ("generations") of kink solutions in an SU(N)XZ₂ field theory and identified their stability properties. We also looked at the space of SU(5) monopole solutions and found an exact triplication for n=1 monopoles. In the context of the dual standard model this hints at a possible explanation of the origin of three families of particles in the Standard Model.

In the area of stochastic quantum mechanics we obtained exact analytic formulae for the dynamics of the wave function and associated physical observables. This is one of the most exciting developments in the subject, and we are now able to carry out simulation studies for the time evolution of the wave function of any quantum system. We have also extended the stochastic approach to study the feasibility of nonlinear quantum systems. Finally, it is known that, if the Hamiltonian of a system is invariant under space-time reflection symmetry, then it may possess a real spectrum. We have constructed quantum theory based on such a Hamiltonian, showing the self-adjointness of such complex, non-Hermitian Hamiltonians. In particular, we found a previously unknown symmetry in quantum mechanics, which has the interpretation of a charge operator, whose properties are yet to be explored fully.
Causal set theory has also been the subject of much study by Garcia and collaborators. In particular, they have constructed a classical stochastic growth model in which the partial order is formed sequentially through classical probability rules. A key step is the construction of a measure on the space of causal sets: this measure could also be a key ingredient in applying quantum category theory to give a quantum theory of causal sets.

In connection with both of the endeavours mentioned above (ie, ‘discrete quantum spacetime structure’ and ‘causal set theory’), Raptis, in collaboration with Zapatin, has worked on a combinatorial-algebraic approach to quantum spacetime topology. He has also been collaborating with Mallios, on applications of the latter’s sheaf-theoretic Abstract Differential Geometry to causal sets and discrete Lorentzian quantum gravity. The algebraic structures involved have been also applied to certain structural issues in quantum computation and networks theory.

There has been much work on the application of the consistent-histories approach to quantum theory in the context of quantum field theory and quantum gravity. In particular, Savvidou has developed a history version of quantum field theory, which has been extended by Isham and Savvidou to include the quantisation of the foliation vector. However, the most important advance has been Savvidou’s construction of a history theory of general relativity, which offers the possibility of a new, space-time based approach to quantum gravity and quantum cosmology.

One of the most important recent developments in theoretical high energy physics is the AdS/CFT correspondence. Recent work has been aimed at generalising this to theories with less supersymmetry or to non-conformal theories, which are much closer to realistic models. The main focus of our work in this area has been the study of fractional 3-branes on conifolds, which are dual to a class of confining N=1 supersymmetric gauge theories.

Resolution of singularities has also been studied at the supergravity level through an analysis of asymptotically conical spacetimes with Heisenberg symmetries. These solutions generalise the Eguchi-Hanson metric, and we are in the process of applying them to dimensional reductions on branes in infinite transverse dimensions for cosmological applications.

While most of the previous investigations of the AdS/CFT duality were based on a supergravity approximation, string alpha-prime corrections also encode important information about the strong-coupling expansion on the gauge theory side. We have investigated the effect of the leading string corrections to the supergravity low-energy effective action for a 3-brane/conifold solution. We also gave a general argument that supersymmetric solutions solving BPS conditions at the supergravity level continue to satisfy a 1st order renormalization-group type system of equations with extra “source” terms encoding the string corrections.

Another important direction of research in string theory is the investigation of mechanisms for supersymmetry breaking and the stability of non-supersymmetric vacua. Useful insights are gained by the study of exactly solvable string models such as on Melvin magnetic flux tube backgrounds. We have shown how to reformulate the problem of the closed string (winding mode) tachyon instability in terms of the instability of a related gravitational background. This allows one to consider its evolution purely in field-theoretic terms. We have also found generalisations of the
AdS3 anomalous dimensions of operators exist with varying amounts of unbroken supersymmetry. We have clarified how Supergravity plane-wave solutions which are limits of AdS5 theories in plane-wave backgrounds found explicitly the spectra of string Using light-cone gauge, we have large R-charge limit suggested by Berenstein, Maldacena and Nastase. The corresponding string theory is defined in a maximally-supersymmetric plane-wave background. Using light-cone gauge, we have found explicitly the spectra of string theories in plane-wave backgrounds which are limits of AdS5×S5 and AdS3×S3.

Supergravity plane-wave solutions exist with varying amounts of unbroken supersymmetry. We have clarified how the worldvolume picture corresponds to the supergravity bulk picture through a comparison of unbroken worldvolume supersymmetry in physical and in light-cone gauges.

Relations between supergravity and super Yang-Mills have been clarified in a study of the divergences of maximally supersymmetric theories. Differences between unitarity-based predictions of the order of onset of ultraviolet divergences and the predictions of standard superspace Feynman diagram analysis have now been resolved in the maximal super Yang-Mills case. The difference disappears when one employs an N=3 harmonic superspace formalism of the N=4 theory. Although there is not so far an analogous N=7 formulation of maximal N=8 supergravity, there is a hint that such a formulation might exist.

We have developed (extending work of Gubser, Klebanov and Polyankov) a semiclassical approach to the quantisation of closed strings in AdS5×S5, demonstrating that the anomalous dimensions of operators corresponding to rotating strings in AdS have logarithmic dependence on spin not only at the classical string level but also when including quantum string corrections.

In M-theory, the antisymmetric tensor gauge transformations have a topologically non-trivial extension that probes the cohomology of the underlying spacetime and which is intimately related to the charge spectrum of branes. We have studied the relation between bulk and worldvolume forms of these using relative cohomology, showing how the large gauge transformations are preserved by the anomaly-cancelling mechanism of M-theory.

Brane-world models offer an approach to cosmology from string theory. We have pioneered the study of Horava-Witten geometries in D=5 spacetime. We have studied the dynamics of the radion mode involved in inter-brane forces and the possible potentials that could arise for this mode. We have studied models incorporating brane gasses in the early universe that may provide a dynamical mechanism for the four-dimensionality of observable spacetime. We have also studied possible mechanisms for inflation arising from D-brane annihilation.

Cosmology and Varying Constant Theories

S. Alexander, R. Bean, T. W. B. Kibble, J. Levin, J. Magueijo, M. Parry, and L. Pogosian

The cosmic microwave background (CMB) is a unique tool for testing theories of the early universe. One of the major predictions made by structure formation theories is that the CMB density fluctuations should be Gaussian. Imperial has played a leading role in the quest for methods for testing this hypothesis. Besides the development of data analysis software in collaboration with investigators at Cambridge MRAO, and CITA, we analysed a number of actual datasets, most notably the Maxima-Boomerang dataset. The Group hopes to keep this leading position when MAP data is released in the very near future, though shortage of manpower could prevent this from happening.

Quintessence is a popular explanation for the acceleration of the Universe. One may then ask what are its implications for theories of galaxy formation and CMB anisotropies. This question was tackled in great detail by our Group, in the context of various coupled and uncoupled quintessence scenarios that we originally proposed. The Group also investigated the possible interactions of a quintessence field and the formation and evolution of supermassive black holes. It was proposed that supermassive black holes may be primordial black holes that have eaten too much quintessence.

Over the past two years our Group was instrumental in establishing a framework for relating the theory and observations of a varying fine structure constant. Our work has led to a large literature exploring the different implications of a varying alpha in all sorts of astronomical and laboratory contexts. The Group also has related these observations to the current acceleration of the universe, showing that acceleration tends to stabilise time-varying constants, thus relaxing many observational constraints. Implications for CMB anisotropies were also studied by several members of the group.

Finally, we showed how thermal fluctuations in varying speed of light (VSL) scenarios could produce the right spectrum for explaining CMB fluctuations and galaxy clustering properties. One of the highlights of the Group's research was the discovery that varying constant theories, and in particular VSL theories, may play an important role in the quantisation of gravity. Our work on the non-linear realisations of the Lorentz group has triggered much subsequent work on methods for implementing invariant quanta of space and time. But, more interestingly, it was shown that such VSL quantum gravity theories may explain the presence of ultra high energy cosmic rays. This could open the door to observational quantum gravity.
**Undergraduate Teaching**

**Director of Undergraduate Studies:** Professor A. R. Bell, Dr R. C. Thompson (from September 2003)

**Senior Tutor:** Dr R. J. Forsyth

**Admissions Tutor:** Prof. W. G. Jones

**School Liaison:** Dr J. Hassard

The Blackett Laboratory, the largest Physics Department in the UK, welcomes about two hundred new undergraduate students each year. We offer three year and four year undergraduate degree programmes designed to match the pre-university experience of students from the UK, Europe and overseas. These degree programmes lead to either the BSc or the MSci degrees of the University of London (under special regulations for Imperial College).

**The Degree Programmes**

Entry is onto five degree programmes, and the course structure allows easy transfer between most of the programmes in the early years.

**Three Year Programme**

- BSc Physics

**Four Year Programmes**

- BSc Physics with Studies in Musical Performance
- MSci Physics
- MSci Physics with a Year in Continental Europe
- MSci Physics with Theoretical Physics

The Department also offers a four year BSc in Physics with a Year in Continental Europe, and a three year BSc in Physics with Theoretical Physics, but students are not normally admitted to these programmes in Year 1.

The Department aims to provide all students on all degree programmes with courses of the highest quality giving students the opportunity to develop their knowledge and understanding of Physics to a level which equals or exceeds that offered by any other university in the UK. We are carrying out a major review of our programmes to ensure that they are up-to-date and meet changing expectations regarding international (particularly European) standards. The Departmental Staff/Student committee is very active and makes an important contribution to the design of the curriculum and to continuing improvements in teaching.

All programmes start with a firm foundation in core physics and mathematics followed by a broad and flexible range of options in the later years. Courses are lectured by experts in the field, and the breadth and depth of research activity in this large department enables us to bring students to the frontiers of research in a wide range of specialities in physics. The department received the top grade of 5* in the 2001 research assessment and a teaching quality assessment of ‘excellent’. The lecturers are drawn from our nine internationally recognised research groups:

- Astrophysics
- Condensed Matter Theory
- Experimental Solid State
- High Energy Physics
- Photonics
- Plasma Physics
- Quantum Optics and Laser Science
- Space and Atmospheric Physics
- Theoretical Physics.

We also draw on expertise in other departments to offer Mathematics and Biophysics courses. Final year projects are offered in all these research areas, providing an opportunity for students to work alongside academic staff, research fellows, research assistants and postgraduate research students. In the first three years, students receive tutorials in groups of four from academics and other researchers.

**Occasional Students**

Each year about thirty students from universities throughout Europe and further afield come to study in the Department for selected final year courses and laboratory work. Most come under ERASMUS/SOCRATES exchange student programmes. These Occasional Students, and those European and International students enrolled on our three and four year degree programmes, greatly enhance the cosmopolitan ethos of the Department.

**MSci or BSc?**

Broadly speaking, students aiming for a career as a professional physicist or wishing to understand physics at the frontiers of research should follow the MSci programme both for the additional content and also for the opportunity to develop professional skills and undertake a major project. The MSci is the normal route to a PhD. The BSc is aimed at a wide variety of students who wish to follow careers outside specialised research. Many employers value the numeracy and problem-solving skills of Physicists. For example, many physics graduates find their degree an excellent platform for a career in finance. Some students choose the three year BSc as a rapid and less extended route into careers based on physics in industry and public service. Others aim for a research career in physics by taking the BSc followed by a specialist MSc.

**Courses in the first year cover:**

- Electricity & Magnetism
- Mechanics
- Relativity
- Structure of Matter
- Vibrations & Waves
- Quantum Physics
- Professional Skills for Physicists
- Mathematics I
- Mathematical Physics Theory
- Physics Laboratory I
- Physics Short Experiments and Project I
Weekly seminar groups are a novel feature of the first year. These include group projects, development of problem solving skills, and exploration of research articles, web sites and research data.

In the First and Second Years we teach computing in C++, a valuable skill which is attractive to future employers. During the first few weeks of the first term students are given a four hour “hands-on” introduction to computing and current application packages.

For most students, the first year practical class consists of four week sessions on optics, electronics and computing. They may then choose between Maths Physics Theory and more laboratory. For those choosing lab, six weeks are spent on short experiments designed to complement the first year physics lectures. The majority of students then carry out a project working in small groups culminating in two open days in which staff, other students and sixth-formers view poster presentations on their project.

The physics lecture courses are examined during the third term.

**The Second Year**

Second year core courses cover:-
- Quantum Mechanics I
- Thermodynamics
- Statistical Physics
- Mathematical Physics
- Electromagnetism
- Electrons in Solids
- Optics
- Applications of Quantum Mechanics
- Statistics of Measurement
- Professional Skills seminars
- Physics Laboratory II

BSc and MSci Physics candidates choose a Level 2 option from:-
- Sun, Stars and Planets
- Physics Applied to Medicine
- Mathematical Methods
- Language

Second year laboratory work includes experiments on spectroscopy, diffraction and holography, interferometry, transmission lines and thermal waves, radioactivity, solid state, operational amplifiers and computing. Emphasis is placed on the development of a range of experimental techniques as well more general professional skills such as writing reports, keeping a laboratory note book, and error assessment.

**The Third Year**

MSci candidates take core courses in:-
- Nuclear and Particle Physics
- Solid State Physics
- Atomic and Molecular Physics
- Professional Skills
- Laboratory III

BSc candidates take Nuclear and Particle Physics and at least one of the other core lecture courses. They may take one or two terms of laboratory, and all have to complete a project, which may be laboratory or library based, or theoretical.

Both MSci and BSc candidates complete their third year with a selection of Level 3 options. The more theoretical physics lecture courses are marked with a (T):-
- Computational Physics  (T)
- Group Theory  (T)
- Dynamical Systems & Chaos  (T)
- Condensed Matter Theory  (T)
- Instrumentation
- Astrophysics
- Plasma Physics
- Molecular Biophysics
- Lasers, Optics and Holography
- Advanced Classical Physics

Students may also choose up to one Level 2 option (see above) and up to one Level 4 option (see below). They may also include one of the following courses:-
- History of science
- History of technology
- Philosophy I
- Modern literature and drama
- European history
- Politics
- Communication of science (practical)
- Science, communication and society
- History of medicine
- Ethics of science and technology
- Roman history
- Art and nature

**The Fourth Year**

In their fourth year MSci students complete a major project with a research group. This gives students an opportunity to get to grips with an extended project that lasts the whole year and relates to current research activities. In some cases, the project results in the publication of a research paper. Under the guidance of a lecturer, students learn how to set goals and plan their work to achieve them. They learn to research literature, to design an experiment or develop computer software, and to present their results in oral and written presentations.

The project is coupled to the Research Interfaces course which develops professional skills. This course explores the subjects of project management, written communication, financial management and spoken communication. An aim is to give students a working knowledge of the vocabularies relating to research in universities and industry.

At present, students choose two further option courses from a list of eighteen options and select three options “with advanced study”. Following the present curriculum review, affecting the fourth year in 2004-05, MSci students will choose a selection of Level 4 options, and may select one Level 3 option (see above). The Level 4 options will be:-
- Biophysics of Nerve Cells & Networks
- Space Physics
- Devices
- Optical Communications
- Quantum Optics
- Cosmology
- General Relativity
- Atmospheric Physics
- Photonics
- Particle Physics  (T)
- Quantum Field Theory  (T)
- Unification  (T)
- Computational Physics  (T)
- Quantum Statistical Physics  (T)
Students who choose to follow this four year MSci programme concentrate on the more theoretical options. In their first year they take an extra formal mathematical physics course instead of project work and in their second year the Mathematical Methods option. In Year 3 these students must take Advanced Classical Physics instead of laboratory. The fourth year project is theoretical and they also take a specified number of theoretical options.

The Year in Europe Programmes

The MSci in Physics with a Year in Europe is of four years duration with the third year being spent in a research group in a host university in continental Europe. Year in Europe students have derived great benefit and enjoyment from this opportunity to widen their experience. They usually go to Europe on SOCRATES / ERASMUS exchange programmes.

Students are visited twice during their year abroad by a member of staff who normally is very familiar with the host country and university.

Students carry out a research project in a research group. They are assessed on their written project report, a report from their supervisor, and an oral presentation in the host language.

In addition to the research project, students attend physics lecture courses and sit examinations, written or oral, in the host language. As preparation for their year abroad they take language courses in both their first and second years and are recommended to take Mathematical Methods in their second year.

In their fourth year MSci Year in Europe students sit the Comprehensive Papers, and take Nuclear and Particle Physics, the Research Interfaces course and choose from a range of options drawn from the third and fourth year programmes. The research project completed abroad counts as their MSci project.

We have established links with host universities in France, Germany, Italy, Spain and Switzerland. These are: Université de Paris XI (Orsay), Ecole Supérieure de Physique et de Chimie Industriel (Paris), Ecole Polytechnique Fédérale de Lausanne, Institut National Polytechnique de Grenoble, Universität Erlangen-Nürnberg, Universität Freiburg, Universität Hamburg, Technisches Universität Karlsruhe, Universität degli Studi di Padova, Università degli Studi di Trento, Universidad de Valencia, Universidad de La Laguna (Instituto de Astrofísica de Canarias), and Universidad de Cantabria (Santander).

Each of these universities has high standing and extensive research activity. Some have exceptional facilities in particular research fields. For example, La Laguna is excellent for Astrophysics because of the siting of many astronomical telescopes in the Canary Islands.

The musical life of Imperial College has always been strong and many physics students have demonstrated high ability in musical performance. The joint degree programme with the nearby Royal College of Music is for physics students who can also reach the RCM's stringent admission standards in musical performance. This programme provides students with a high quality honours BSc qualification in physics while providing musical training to the highest international standards. The music component mainly consists in high level performance tuition by the Professors of the Royal College of Music but also includes musical theory and history of music. The Imperial College Director of Music is actively involved with this course. Students on this programme have given public recitals, performed as concerto soloists, and won national competitions such as Young Musician of the Year.

The Year in Europe Programmes

| Year in Europe Host Institutions |

- **FRANCE**
  - Paris
  - Strasbourg
- **GERMANY**
  - Berlin
  - Hamburg
- **SWITZERLAND**
  - Geneva
- **ITALY**
  - Milan
  - Padova
- **SPAIN**
  - Madrid
  - Barcelona
  - Valencia
- **UNITED KINGDOM**
  - London
  - Edinburgh

We have established links with host universities in France, Germany, Italy, Spain and Switzerland. These are: Université de Paris XI (Orsay), Ecole Supérieure de Physique et de Chimie Industriel (Paris), Ecole Polytechnique Fédérale de Lausanne, Institut National Polytechnique de Grenoble, Universität Erlangen-Nürnberg, Universität Freiburg, Universität Hamburg, Technisches Universität Karlsruhe, Universität degli Studi di Padova, Università degli Studi di Trento, Universidad de Valencia, Universidad de La Laguna (Instituto de Astrofísica de Canarias), and Universidad de Cantabria (Santander).

Each of these universities has high standing and extensive research activity. Some have exceptional facilities in particular research fields. For example, La Laguna is excellent for Astrophysics because of the siting of many astronomical telescopes in the Canary Islands.
Our degree programmes contain a most valuable and unique component: the two comprehensive examination papers. These carefully constructed papers are designed to test our students’ ability to apply the core physics taught in earlier years of the course and students are prepared for this kind of problem solving through special tutorials. Most candidates complete these papers in their third year.

Applications for our undergraduate courses are received through the UCAS system from all parts of the world although most are from the UK. We wish to encourage applications from all sectors, particularly from areas traditionally under-represented in higher education and from other European countries. We are looking for students of high ability and motivation with the potential to do well on our courses. Offers of places are conditional on achieving high grades in physics and mathematics at A-level and in a third subject. The average of the grades of students admitted is significantly above AAB (best 3 A-levels). We also admit students offering the International and European Baccalaureate, German Abitur, US Advanced Placement examinations and school leaving qualifications from many other countries.

The percentage of women undergraduates admitted onto our course has increased over recent years and in 2002 was over 26%, which significantly exceeds the national average. This increase has been helped by the College’s ‘taster’ courses called WISE (Women into Science and Engineering) which we operate in July each year.

Our students have wide interests and abilities, particularly in music, the arts and sports, as well as being among the most talented in the land in physics. They go on to a wide variety of careers after graduation and a recent European wide survey has indicated that their rating of both the employment potential of their degree and of the quality of their university experience are much higher than the European average.

All applications receive careful attention and those applicants that appear to be well suited to our courses are invited for a visit and interview. These visits take place in small groups between early November and early March and consist of a tour of the campus, usually including a Hall of Residence, guided by an undergraduate, followed by a meeting with the Admissions Tutor or one of his colleagues on the admissions team. This is designed to give applicants information about the courses and the facilities and also about life in Imperial College and London. There is then a tour around the department followed by a short individual interview. The latter helps us to get to know the student as an individual and is mainly concerned with interests and motivation. It also enables applicants to raise questions of particular interest to them.

Our high international profile is manifested in many ways, not least through our membership of several strategic alliances with major universities in Europe (e.g. CLUSTER and the IDEA League) and with the presence of large numbers of students from other European universities studying with us for one year as exchange students. The Department is greatly enhanced through the rich cultural and national diversity of our students.

Schools Liaison

School liaison is a high priority within the Department, and we offer visits to schools and “guided tours”. We also offer places to a number of school students undertaking work experience training. We have extended our reach geographically: for example, Physics has been featured in the annual Imperial College recruitment visit to Hong Kong.

The Department, in association with the College and the University of London, has an extensive range of out-reach programmes. These are free and are designed to introduce physics to potential undergraduates. The most popular is the Open Day, focussed around a display by First Year students of their project work, and held around the third week of June. There are also various Masterclasses held at various times during the year. The highly popular two-day Women in Science and Engineering courses, held in July, are specifically designed to encourage women students to consider a degree course in one of the science or engineering disciplines.
Director of Postgraduate Studies: Dr Julia Sedgbeer

The Physics Department is one of the most prestigious postgraduate schools in Physics in the UK. In terms of research it uniquely covers the most comprehensive range of important experimental and theoretical research fields. These extend from astronomy, space and plasma physics to high energy, theoretical and atomic physics. Solid state, laser physics, applied optics and photonics have wide applications, while fields such as quantum information theory may lead to exciting new applications. There are close links with the biophysics research group (part of the Department of Biological Sciences), which is also housed in the Blackett Laboratory. There are many examples of international and industrial collaboration involving our nine research groups. There are also interdisciplinary centres where researchers from different groups or from different Departments collaborate closely to benefit from each other's expertise. The Department has extensive facilities and a tremendous range of research topics available to postgraduate research students.

Information about the research being undertaken in the particular groups and centres can be found under their sections elsewhere in this report; further details can be obtained from the individual Heads of Group (see page 49).

The Department provides facilities and supervision for students to engage in research work leading to a higher degree of the University of London (MPhil or PhD), and to the Diploma of the Imperial College (DIC). About 60 postgraduate research students join the Blackett Laboratory each year, the majority being UK students with about 25% from other EU countries and about 15% from overseas. The normal qualification for acceptance for research training is a first or second class honours degree in Physics or a related subject. The usual length of registration for a PhD degree is three years.

In addition to research training, the Department offers postgraduate taught courses leading to the MSc degree of the University of London and the DIC. The Department offers two MSc courses: Optics and Photonics and Quantum Fields & Fundamental Forces. Further details of these MSc courses are given below.

The new Graduate School of Engineering and Physical Sciences (www.imperial.ac.uk/gradeeps/) has been established to develop and enhance the academic experience of graduate students at the College. It provides training programmes and workshops in professional and other skills, undertakes quality assurance of graduate programmes, organises events, such as guest lectures and symposia, and promotes career opportunities for graduate students.

Very few institutions worldwide are able to offer such a wide range of opportunities in postgraduate physics. Further information can be found in the Postgraduate Study in Physics booklet, (email: admissions@imperial.ac.uk) or on www.imperial.ac.uk/publications/pgb/

General information about graduate studies at Imperial College London can be seen at www.imperial.ac.uk/pgoptions.

MSc in Optics and Photonics

The MSc course in Optics and Photonics has been running since October 2001 and draws on the skills of staff actively involved in optics research. The title reflects the fact that the course covers both the traditional areas of optics, which are of key importance to the application of optical techniques, and the emerging areas of photonics, notably optical communications. The course aims to provide the professional skills in optics which are in demand by industry and academia.
There are a large number of job opportunities in optics and photonics throughout the UK and the rest of Europe, not only in optical communications but also in many other areas of applied photonics.

The 12-month MSc Optics and Photonics course consists of lectures, laboratory experiments and a project. In the first term, there are four Foundation lecture courses in Information and Telecommunications, Imaging, Lasers, and Optical Measurement and Devices. In addition, there are sessions dedicated to the development of professional skills. There are occasional seminars on the application of optics technology in industry, together with seminars on research and development in universities and industry. In the second term, a number of option courses are offered, including Optical Fibres, Advanced Optical Communications, Optical Design, Optical Design Laboratory, Optical Fibre Sensors, Laser Optics, Laser Technology, and Optical Displays.

The laboratory experiments cover a wide range of subjects and are spread over approximately 54 half-days in the first and second term.

The project lasts from mid-May to mid-September, and many projects can be carried out in industry. Examples of recent projects are "A new method of producing unidirectionality in solid-state ring lasers", "Polymer/nanocrystal blends for solar cells", "Femtosecond pulse shaper using a spatial light modulator", "Adaptive optics for the human eye", "MEMS based digital filter", "Optical modelling and optimisation of organic LED structures" and "Fluorescence lifetime imaging applied to microscopy".

There are 20 EPSRC funded places for suitably qualified UK students. Funding is also available to cover the fees for suitably qualified students from other EU countries. Almost 50 companies have backed the course with offers of support in kind equivalent to £1.5M over the five years of funding.

MSc in Quantum Fields and Fundamental Forces

The Theoretical Physics Group runs this very successful MSc course, attracting around 15 students annually. It is normally a one-year course but can also be taken part-time over two years. A series of lecture courses occupies the year up to May and students spend the summer on a project leading to the writing of a dissertation. The course is intended to bridge the gap between undergraduate-level work and the research frontier in theoretical physics. Many successful students have gone on to do a PhD either at Imperial College London or at another major university. Unfortunately, no financial support is available for students attending the course.

The lecture courses currently being offered are:

Compulsory lecture courses:
- Quantum electrodynamics
- Electroweak unification
- Advanced Quantum Field Theory

Optional courses:
- Supersymmetry
- Cosmology and Particle Physics
- Topics in Quantum Gravity
- String Theory
- Differential Geometry
- Special Topics (short specialist courses on topics of current interest)

Available undergraduate courses:
- Quantum Mechanics
- Group Theory
- Dynamical Systems and Chaos
- General Relativity

Courses are offered subject to staff availability; certain courses may not be offered in a given academic year.

Students are assessed by examinations and a project dissertation. The examinations are on the compulsory courses and on four optional courses, which may include up to two undergraduate options. Examinations on all the courses are held in May. There are also informal tests on the compulsory courses in January.

MSc students are also encouraged to attend the regular weekly seminars at which visiting speakers present recent research results, as well as internal seminars by research students. These are supplemented by an inter-Collegiate programme of weekly seminars on string theory and related subjects.
**PhD Degrees awarded in the Department in 2002**

### Astrophysics

Supervisor: Prof. M Rowan-Robinson

A. M. Begley “Particle Cascades in Quasar Central Engines.”
Supervisor: Prof. J J Quenby

A. Meli “Particle Acceleration at Relativistic and Ultra-relativistic Shock Waves”
Supervisor: Prof. J J Quenby

Supervisor: Dr K Christensen

S. O’Brien “Artificial Magnetic Structures.”
Supervisor: Prof. J B Pendry

R. Vardavas “Fluctuations and Scaling in 1D Irreversible Film Growth Models.”
Supervisor: Prof. D Vvedensky

### Condensed Matter Theory

Supervisor: Dr L F Cohen

### Experimental Solid State Physics

M-L. Aspinwall “Measurement of the exclusive branching fractions and Asymetries of $B \rightarrow \pi K$ at BaBar.”
Supervisor: Dr P D Dauncey

D. U. Bauer “A study of $B^0 \rightarrow J/\psi \phi$ in the DØ experiment and an example of HEP technology transfer”
Supervisor: Dr J F Hassard

D. Bowerman “Study of the rare decay $B^0 \rightarrow \pi^0 \pi^0$ at BaBar”
Supervisor: Dr P D Dauncey

R. A. Illingworth “Development of Trigger Software for the silicon and fibre trackers and a study of $B$ Meson Lifetimes for the DØ Experiment.”
Supervisor: Dr J F Hassard

D. Smith “Analysis of the Flavour Changing Neutral Current $b \rightarrow s$ at BaBar”
Supervisor: Dr J A Nash

### Optics - Photonics

Z. Ansari “Whole-field, real-time Photorefractive Holography for Imaging through Turbid Media using Sources of Diverse Spatial and Temporal Coherence”
Supervisor: Prof. P M W French

F. Koch “Linear and Non-linear Characterization in Optical Fibres”
Supervisor: Dr J R Taylor

D. G. Moodie “Electroabsorption Modulators for Telecommunications Networks.”
Supervisor: Dr J R Taylor

P. C. Reeves-Hall “Optical Fibre Based Pulse Sources and Amplifiers.”
Supervisor: Dr J R Taylor

### Optics - Quantum Optics and Laser Science

E. J. Grace “Optimisation of Kerr-lens mode-locked Lasers”
Supervisors: Prof. G H C New & Prof. P M W French

I. Kucukkara “Electromagnetically Induced Transparency in Four Wave Mixing Scheme.”
Supervisor: Prof. J P Marangos

K. J. Mendham “Energetic Cluster Explosions in Intense Femtosecond Laser Fields”
Supervisors: Dr J W G Tisch & Prof. J P Marangos

S. S. Virmani “Entanglement Quantification & Local Discrimination.”
Supervisor: Prof. P L Knight

### Theoretical Physics

M. Asprouli “Real Time Effective Actions in Quantum Field Theories”
Supervisor: Dr R J Rivers

R. E. Bean “Scalar Field Cosmologies and their Observational Implications.”
Supervisor: Dr J C Magueijo

A. Filippi “The Multiplicative Anomaly and Zeta-Function Regularization in Quantum Field Theory”
Supervisor: Dr R J Rivers

H. B. Sandvik “Varying Fundamental Constants in Cosmology”
Supervisor: Dr J C Magueijo

### Experimental Solid State

P. M. Hudson “Scanning Probe Microscopy Studies on Colossal Magneto resistive Materials.”
Supervisor: Dr L F Cohen

### Space and Atmospheric Physics

Supervisor: Prof. J E Harries

Supervisor: Prof. P J Cargill

P. J. Sagoo “Changes in the Greenhouse effect of the earth from measurements of thermal emission spectra in 1970 and 1997”
Supervisor: Prof. J E Harries

A. C. Tomsett “Time series Analysis of United Kingdom Precipitation and its Extremes”
Supervisor: Dr R Touni

### Experimental Solid State

P. M. Hudson “Scanning Probe Microscopy Studies on Colossal Magneto resistive Materials.”
Supervisor: Dr L F Cohen
The following grants, valued at over £15.0 million, were initiated during 2002.

**Air Products and Chemicals Inc.**
**Bradley, D;** New class of materials for organic light emitting devices. £31,750.

**Astrium Gmbh**
**Balogh, A;** Double star magnetic field investigation. £280,955.

**Balogh, A;** Double star pre-integration. £487,797.

**BP International Ltd.**
**Bradley, D, and Jones, T;** OSCER-Organic Solar Cell Research. £750,000.

**CCLRC**
**Kellock, S;** Co-ordinaton of gist activities of the GERB international science team. £107,291.

**Commission of European Communities**
**Cargill, P;** Theory observation and simulation of turbulence in space plasmas. £132,000.

**Caplin, D;** SCENET 2. £2,000.

**Murray, R;** HYTEC. £124,461.

**Dainty, J C;** SHARP-EYE. £898,993.

**Pendry, J;** Development and analysis of left handed materials (DALHM). £156,568.

**Meikle, P;** The physics of type Ia explosions. (Type Ia supernovae). £67,941.

**Department Of Trade & Industry**
**French, P;** Functional bioimaging using fluorescence lifetime imaging. £920,664.

**Engineering & Physical Sciences Research Council**
**Hinds, E;** Measurement of electron electric dipole moment. £40,239.

**Chittenden, J;** Microscopic X-pinch plasmas of extremely high density and temperatures: A computational investigation. £100,475.

**Torok, P;** EPSRC Advanced fellowship: Interaction of electromagnetic waves with complex specimen structures in optical microscopy and conoscopy. £28,029.

**Bradley, D;** Basic Technology: Next generation artificial vision systems: reverse engineering human visual processes. £240,557.

**Caplin, D;** Investigation of the magnetic properties of potential spintronic ferromagnetic materials. £37,550.

**Hinds, E;** The UK cold atoms network: UKCAN. £49,625.

**Barnham, K;** Visiting fellowship for Dr Massimo Mazzer to study Strain-balanced quantum well solar cells. £60,872.

**Marangos, J;** Modulation of femtosecond laser pulses by molecular coherence. £130,749.

**Phillips, C;** Terahertz sideband generation and quantum cascade lasers. £53,482.

**Bradley, D, De Mello, A and De Mello, J;** Polymeric detection systems for micro analysis. £294,748.

**Bradley, D, Jones, T, and Steinke, J;** Carbon based electronics: A national consortium. £142,921.

**Bell, A;** Fokker-planck simulations of transport and absorption in laser-produced plasmas. £164,976.

**European Space Agency**
**Sumner, T;** Inertial sensor charge management system for LISA. £189,100.

**Sumner, T;** Inertial sensor charge management system for LISA. £189,100.

**MoD (AWE plc)**
**Haines, M G and Chittenden, J;** The William Penney Fellowship for Dr J Chittenden. £31,200.

**National Physical Laboratory**
**Segal, D;** Advanced optical flywheel oscillators. £54,098.

**Natural Environment Research Council**
**Toumi, R;** HIMAP: High Himalayan atmospheric pressure. £30,346.

**Pickering, J and Harries, J;** EMERALD- II Egret Microphysics experiment with radiation, Lidar and dynamics in the tropics. £99,774.


**Harries, J;** New methods to estimate grid or catchment evaporation using satellite and ground-based measurements. £156,557.

**Harries, J and Toumi, R;** The global distribution, variability and radiative-climatological impact of atmospheric water vapour. £141,239.

**Particle Physics & Astronomy Research Council**
**Bowerman, D;** Measurement of the CP unitarity triangle angle alpha through the systematic study of rare B meson decays to three pions at BaBar. £95,471.

**Britton, D;** GridPP project manager costs. £82,012.

**Kalkkinen, J;** M-Theory solutions and geometry. £120,394.

**Hinds, E;** eEDM:Measurement of the electron electric dipole moment. £191,840.
Dainty, J C; A complete toolkit for adaptive optics. £341,359.

Rowan-Robinson, M; Infrared astronomy and cosmology. £900,730.

Thompson, M; Measuring oscillations of nearby stars (MONS). £4,033.

Dornan, P; Study of elementary particles and their interactions. £2,582,591.

Pickering, J; Astrophysical laboratory spectroscopy: improving the atomic data for astrophysics by high resolution Fourier transform spectroscopy. £110,996.

Dainty, J C; Compact wavefront sensing for the assessment of the refractive state of the eye. £153,951.

Dainty, J C and Paterson, C; High angular resolution imaging. £165,452.

Cargill, P; Studies of solar and space plasmas Fellowship: Prof Cargill. £108,994.

Meikle, W P; The origin, explosion and fate of core-collapse supernovae. £167,233.

Balogh, A; Research in solar, space and planetary physics and instrument development at Imperial College. £1,313,070.

Butterworth, I; Visit by Professor Thomas Ferbel. £13,436.

Dainty, J C and McCall, M; Laser guide star adaptive optics for the visible. £132,762.

Drew, J; ICSTM Astrophysics short term academic visits programme. £14,186.

Dornan, P; PPARC support for EU Datagird. £421,748.

Sumner, T; Technology development for gravitational wave space missions- internal sensor charge control. £81,041.

Royal Society
Beige, A; Royal Society Fellowship. £220,176.

Pendry, J; String theory, quantum field theory, quantum gravity. £55,000.

Sandia National Laboratories
Chittenden, J and Lebedev, S; Experimental and computational studies of wire arrays. £85,000.

UKAEA
Cowley, S; PhD student to work in the field of stability analysis and diagnostic tools. £43,969.

University of Bologna
Harries, J; Polarisers for REFIR Far-IR interferometry. £30,602.

University of St Andrews
Bradley, D; Ultrafast photonics for datacomms above terabits speeds. £752,195.

US Army
Plenio, M; Employing noisy environments to support quantum information processing. £56,290.

US Department of Energy
Chittenden, J; Centre for the study of pulsed power driven high energy density plasmas. £225,807.

Wellcome Trust
French, P; Wellcome Trust showcase award. £125,000.
Physics is an international science, and many aspects of our research involve collaborations with colleagues at institutions in the UK and throughout the world. These include:

Air Products and Chemicals Inc., USA
Anglo Australian Observatory, Australia
Aarhus University, Denmark
Astrophysics Research Institute
British Petroleum International, UK
California Institute of Technology, USA
Centre d’Etudes des Rayonnements Spatiaux (CERS), France
CERN
CNR-IFAC, Firenze, Italy
Complutense University, Madrid
Cornell University, USA
Delft University of Technology, The Netherlands
Donostia International Physics Center (DIPC), San Sebastian, Spain
Ecole Polytechnique Federale Lausanne (EPFL), France
Eidgenossische Technische Hochschule (ETH), Switzerland
El Du Pont de Nemours and Company, USA
Endoscan Ltd
ESA-ESTEC, Holland
European Southern Observatory
Free University of Amsterdam, The Netherlands
Free University Berlin, Germany
Free University of Brussels, Belgium
Ghent University, Belgium
GKSS, Germany
Goddard Space Flight Center, USA
Graz University, Austria
Hadley Climate Research Centre
Harvard Smithsonian Center for Astrophysics, USA
Harvard University, USA
Herriot Watt University
Hewlett-Packard Laboratories, USA
High Altitude Observatory, USA
HRL Laboratories LLC, Malibu, USA
INAOE, Mexico

Institute for High Energy Physics, Russia
Institute for Space Research, Austria
Institute for Nuclear Physics, Bulgaria
Institute of Chemical Physics, Spain
Institute of Nuclear Research, Russia
International Space Science Institute, Switzerland
Isaac Newton Group, La Palma, Spain
Jet Propulsion Laboratory, USA
Kentech Instruments Ltd
KFKI, Budapest, Hungary
Kings College London
Los Alamos National Laboratory, USA
Lucent Laboratories
Massachusetts Institute of Technology, USA
Matsushita Electric Works, Japan
Max Planck Institute, Garching, Germany
Max Planck Institute, Heidelberg, Germany
Max Planck Institute, Kattenburg-Lindeau, Germany
MEMC Electronic Materials Inc., USA
Merck Ltd, UK
NASA Langley Research Center, USA
National Institute Standards and Technology, USA
National Physical Laboratory
National Solar Observatory, USA
NRL Washington, USA
Observatoire de Nice, France
Padua Observatory, Italy
Pennsylvania State University, USA
Perimeter Institute, Waterloo, Canada
Philips Research, The Netherlands
Plzen University, Czech Republic
Research Center of Crete, Greece
Royal Meteorological Institute, Brussels, Belgium
Rutherford Appleton Laboratory
Sandia National Laboratory, USA
Scottish Environment and Energy Foundation
Space Telescope Science Institute
Stanford University, USA
Steacie Institute for Molecular Sciences, Canada
Stockholm Observatory, Sweden
Technical University of Braunschweig, Germany
Technical University of Denmark, Lyngby, Denmark
Technical University of Vienna, Austria
Technion, Israel
THALES Paris, France
The Atlantic Alliance
The Dow Chemical Company, USA
Trieste Observatory, Italy
UK Meteorological Office
UMIST
Universidad Autonoma de Madrid, Spain
Universidad de Zaragoza, Spain
Université Louis Pasteur, Strasbourg, France
University College London
University of Arizona, USA
University of Athens, Greece
University of Austin, USA
University of Bangor
University of Barcelona, Spain
University of Basilicata, Italy
University of Birmingham
University of Bologna, Italy
University of Bonn, Germany
University of Braunschweig, Germany
University of Bristol
University of Buenos Aires, Brazil
University of California Los Angeles, USA
University of California San Diego, USA
University of Cambridge
University of Chemnitz, Germany
University of Cologne, Germany
University of Colorado, USA
University of Hampton, USA
University of Hertfordshire
University of Hawaii, USA
University of Kaiserslautern, Germany
University of Leeds
University of Leicester
University of Naples, Italy
University of Neuchatel, Switzerland
We are members of a significant number of European Union and other collaborative programmes, including:

**ACQUIRE**, a European Union training network

**AQEOLOS**, the assessment of the impact of SF6 and PFC reservoir tracers on global warming

**ALEPH** experiment, CERN

**ASTRO-F** consortium

**Australian Network of Excellence on Atom Interferometry**

**Basic Technology Attosecond Programme**

**British Petroleum International (UK) – Imperial College Engineering for Sustainable Development Programme**

**CMS collaboration**

**COCOMO**, a Research Training Network on coherent control of atomic processes

**Consortium for Computational Quantum Many-Body Theory**

**COSLAB**, an ESF Programme on Cosmology in the Laboratory

**D0 Consortium, Fermilab, USA**

**ELAIS survey**

**EPSRC Experimental and Theoretical Studies of Electrical Transport in Organic Electroluminescent Devices Programme**

**EPSRC Polymer Blend Semiconductors Programme**

**EPSRC Retinomorphic Imaging Basic Technology Programme**

**ESF Network on Quantum Information processing**

**ESF-QIT programme on Quantum Information Theory and quantum computation**

**European Union training network on Cold Quantum Gases**

**FASTNET, a European Union training network**

**Framework VI, Nanotechnology; British Council/DAAD ARC programme**

**FERRUM project: oscillator strengths for astrophysics applications**

**HERSCHEL SPIRE consortium**

**HITRAP, An Ion Trap Facility for Experiments with Highly-Charged Ions**

**HYTEC, a CEC Framework V IHP Network**

**IR studies of nearby type II supernovae**

**iSOM, a EU Network on the Information Society as a Complex Network**

**ISD LINK (DTI/EPSRC)**

**Late-time spectroscopy of type Ia supernovae**

**London Centre for Nanotechnology**

**NANOFAb, a European Union training network**

**PLANCK HFI consortium**

**POE, a European Community RTN POWERPLAY, a CEC CSG programme project**

**Ultrafast Photonics Collaboration (UPC IRC)**

**Ultrafast spectroscopy of conjugated polymers**

**SLAM, a programme on Future and Emerging Technologies**

**SWIRE, the NASA SIRTF Legacy Survey**

**QUEST, a European Union IHP Network collaboration on Quantum Optics**

**QGATES, a European Union IST Network collaboration on quantum gates for quantum computing**

**QUBITS**, an IST Network on decoherence in atomic logic elements

**QuIct**, a UK EPSRC Network collaboration on quantum information and coherence

**QUIPROCONE**, a European Union IST Network of Excellence coordinating body on quantum information processing throughout Europe

**QUPRODIS**, a Thematic Network on the Quantum Properties of Distributed quantum systems

**Search for supernovae in starburst galaxies**

**SOLICE, Solar influences on Climate and the Environment**

**Spin Polarised Magnetics Oxides network and Spintronics Network**

**Studies of SN 1987A at very late phases**

**SupIRCam, A tool for understanding the IR light curves of type Ia Supernovae**

**The host galaxies of high redshift type Ia supernovae**

**The Physics of Type Ia Supernova Explosions**

**The progenitors of massive, core-collapse supernovae**

**UKCAN, the UK cold atoms network**

**UK GridPP Project**

**UKIRT Infrared Deep Sky Survey**

**UK Mid-Infrared network**

**UK National Carbon Based Electronics Consortium**
Academic Staff (as of 31st December 2002)

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J C Dainty, PhD

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M W McCall, PhD

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J Nash, PhD

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R J J Rivers, PhD

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R A Smith, BSc, PhD

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R C Thompson, MA, PhD

Atmospheric Physics
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M Neil, BA, PhD

M B Plenio, Dr. rer. nat

D M Segal, BSc, PhD

S J Warren, BA, PhD

K Weir BSc, PhD

J Zhang, BSc, ARCS, PhD, DIC

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D C Brody, BSc, MSc, PhD

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C Paterson, BA, PhD

J C Pickering, BA, MA, PhD, DIC

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J W G Tisch, BSc, PhD

P Torok, DPhil, PhD

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C N Guy, PhD

D K K Lee, BA, PhD

V Moore, PhD

Z Najmudin, BA, PhD

B Sauer, BA, PhD

Y C Unruh, MSc, PhD

V Vedral, BSc, PhD

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P Gill, BSc, DPhil

I Grant, FRS

R Hastie, BSc, MSc

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Sir Martin J Rees, MA, PhD FRS

J C Thompson, MA, PhD
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Theoretical Physics Group
Head of Group: Professor K Stelle
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