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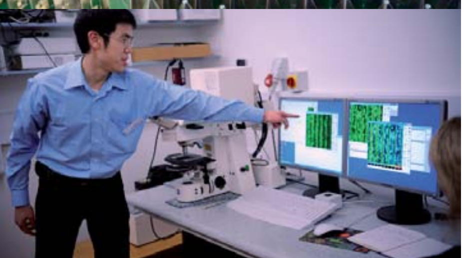
News from the Cavendish Laboratory

Inside...



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The Coolest Place in the Universe

An ultracold refrigerator for quantum computers

Researchers in the Atomic, Mesoscopic and Optical Physics (AMOP) group of the Cavendish Laboratory have succeeded in merging two of the coolest systems in modern atomic and optical physics: atomic quantum gases and single trapped ions. The creation of this new hybrid quantum system, reported in *Nature* in March 2010, opens up fascinating prospects for quantum information processing and the investigation of single impurities in strongly correlated matter systems.

Atomic quantum gases constitute the coldest matter in the universe, approaching within a few billionths of a degree of absolute zero temperature. At these ultralow temperatures, the atoms almost come to a standstill. As a result, this regime allows textbook-like experiments to be carried out, shedding new light on the quantum nature of many-particle systems. The route towards zero temperature in a gas of atoms exploits the mechanical effect of laser light to slow down atoms, followed by evaporative cooling of the atoms in a magnetic trap. Upon reaching temperatures of 100 nanokelvin and below, the experimental efforts are rewarded with the creation of a quantum many-body system of ultimate controllability and accessible to microscopic manipulation.

Because of the tremendous technical challenges, the phenomenon of Bose-Einstein condensation in a gas was only realized 70 years after the initial prediction of Bose and Einstein. The Nobel Prize in physics 2001 was awarded to Eric Cornell, Wolfgang Ketterle, and Carl Wieman who created and investigated the first Bose-Einstein condensates. Since then, a huge upsurge of interest and investment in researches into this novel state of matter has taken place. The initial experiments highlighted the frictionless flow of Bose-Einstein condensates, the presence of quantized vortices, and the observation of matter wave interference effects. Current worldwide investigations are exploring quantum phase transitions, tuneable atomic interactions, and correlation effects between the particles. These recent successes have led researchers to believe that answers to numerous open questions of fundamental physics and new effects will be discovered in the near future. For example, it has been proposed that the physics underlying high-temperature superconductivity may be mimicked using cold atomic gases. In the AMOP group of the Cavendish Laboratory, the new research teams led by Zoran Hadzibabic and Michael Köhl have been working in these lively research fields since 2007.

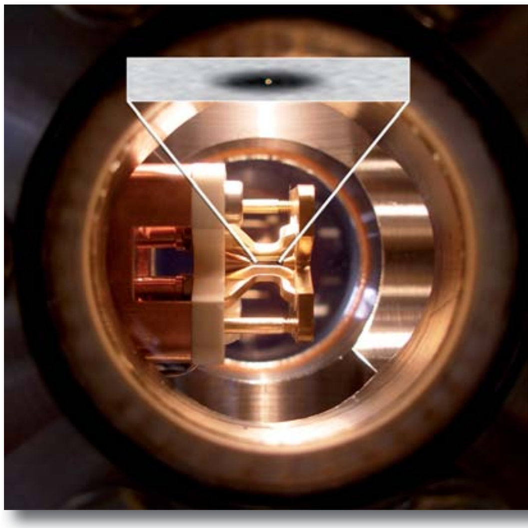

Fig. 1: A view into the ultrahigh vacuum chamber in which the electrodynamic Paul trap for a single ion can be seen. The single ion is trapped in the small horizontal gap, about 0.6 mm width, between the electrodes. The inset shows a photograph of an ultracold neutral atomic gas cloud (dark grey) with the ion schematically indicated.

In parallel with the remarkable progress in research on Bose-Einstein condensates, the investigation of single trapped ions has contributed significantly to our understanding of the quantum mechanical behaviour of small numbers of particles. In particular, universal quantum computing algorithms have been demonstrated with trapped ions, thereby transforming the peculiar features of quantum mechanics, such as quantum entanglement, into a practical application. The upcoming radical technological shift towards quantum computers promises efficient processing of certain computational tasks which are intractable with classical computer technology.

One obstacle hindering the widespread use of such quantum computers up till now lies in

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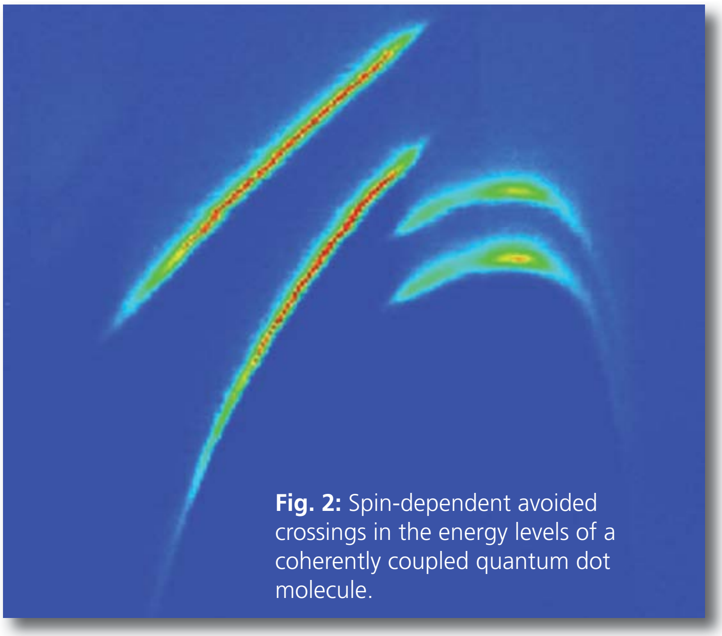


Fig. 2: Spin-dependent avoided crossings in the energy levels of a coherently coupled quantum dot molecule.

the demanding technical requirements. In particular, the unwanted heating of the ion during the computing operations weakens the level of quantum control and the computation has to be regularly paused for cooling. The cooling itself is a very demanding operation requiring state-of-the-art laser systems and precise control of the electromagnetic fields trapping the ions.

In the AMOP group, these two quantum systems have been merged for the first time to form a single hybrid device (Fig. 1). We immerse a trapped ion in an ultra-cold Bose-Einstein condensate. The ultra-cold neutral atom environment constitutes a refrigerator at nanokelvin temperature for the ions and we have successfully observed the ions being cooled. Interestingly, the neutral atom coolant is completely transparent for the lasers that are used to manipulate the ions to perform quantum logic operations (Fig. 2). This offers exciting prospects for continuous cooling of future ion trap quantum computers. In the future, our setup will also allow for the engineering of single impurities in quantum many-body systems with ultimate experimental control.

Michael Koehl

The Legacy of Martin Ryle AMI, ALMA and the SKA

Martin Ryle was awarded the Nobel Prize for physics, jointly with Antony Hewish, for his implementation of the principles of aperture synthesis to construct arrays of radio telescopes with high sensitivity and angular resolution. His culminating achievement was the construction of the Cambridge 5-km telescope, now known as the Ryle Telescope, the first telescope array to create radio images with roughly the same angular resolution as optical telescopes. The same principles are now used in the most powerful radio telescopes world-wide, for example, the Very Large Array in New Mexico and the Australia Telescope National Facility.

The Cavendish Astrophysics Group has continued to exploit and advance these techniques in new contexts. At this very moment, the *Arcminute MicroKelvin Imager (AMI)* at the Lord's Bridge Observatory is carrying out deep surveys at high radio frequencies, not to search for faint radio sources, but for faint 'holes' in the Cosmic Microwave Background Radiation (CMBR) (Fig. 1) . The CMBR is the cooled relic of the hot early phases of the Universe and uniformly pervades all space. If there are regions of hot gas along the line of sight, Compton scattering by the hot electrons slightly shifts the Planck spectrum of the CMBR to higher frequencies, a phenomenon known as the Sunyaev-Zeldovich effect. Such hot gas is found in the vast clouds of intergalactic gas observed in clusters of galaxies. It turns out that surveys of the sky to discover clusters of galaxies by this technique not only provide a key astrophysical tool for their study, but also enable the evolution of clusters of galaxies with cosmic epoch to be determined in some detail, as well as providing tests of the theory of the growth of structures in the Universe. It also turns out that to detect these holes in the background radiation it is essential to remove the point sources and this is achieved using the Ryle Telescope in a compact configuration (Fig. 2, Fig. 3). We await the results of the first deep surveys with considerable anticipation.

At much higher frequencies, the Astrophysics Group is involved in the *Atacama Large Millimetre Array (ALMA)*. John Richer is the UK Project Scientist for this enormous array of 66 telescopes on the Atacama plateau in Chile at an altitude of 5,000 metres. The millimetre and submillimetre wavebands are uniquely important for many different topics in astrophysics and cosmology, in particular for studies of the cold Universe. Many interstellar molecules can be observed and these are key diagnostic tools for star formation in our own and other galaxies. Already molecules have been observed in galaxies and quasars when the Universe was less than 20% of its present age. In addition, the emission of interstellar dust grains, which is intense in the submillimetre wavebands, is a means of detecting and studying the earliest generations of galaxies. The telescope array is now in the course of construction, the overall project scientist in Chile being Professor Richard Hills who is on leave of absence from the Cavendish (Fig. 4). When it is completed in 2012, ALMA is expected to do for millimetre astronomy what the Hubble Space Telescope has done for optical astronomy.

The *Square Kilometre Array (SKA)* is a transformational new radio telescope. Along with ALMA and the planned extremely large optical telescopes, it will provide a revolution in astronomy. The SKA will have two orders of magnitude more sensitivity and be able to map the sky a million times faster than existing radio telescopes. Not only is it firmly based on the techniques of interferometry developed in Cambridge by Martin Ryle, but also the Cavendish are leading the UK design and development effort which is a major part of the global team developing the telescope.

The SKA is designed to address fundamental science questions. Hydrogen is the main atomic ingredient in the Universe and can be observed through a hyperfine transition with rest frequency 1420 MHz. At early cosmological epochs this emission is redshifted to lower frequencies and the SKA will trace the evolution of hydrogen in the Universe from the period when the first galaxies and active galactic nuclei formed, ionizing the hydrogen as part of the process of galaxy formation, to the present time. By determining the position of 10^9 galaxies through different cosmic epochs we will be able to follow the way the seeds of structure identified in observations of the CMBR develop as the Universe expands. Two other experiments will allow us to observe the evolution of cosmic magnetism and test general relativity using pulsars, discovered in Cambridge by Antony Hewish and Jocelyn Bell-Burnell, as natural clocks.

To carry out this exciting science requires an instrument with immense collecting area, the one square kilometre of collecting area of its title, and frequency coverage from 70 MHz to 10 GHz. To achieve this at an affordable cost, one of the Cavendish Astrophysics projects is developing very novel collectors, known as aperture arrays, which use broad-band, static, small antennas (Fig. 5). The signals from each element are digitised directly and we use fast digital signal processing to 'steer' the telescope simply by placing phase gradients between the antennas. The basic idea is not new - it was used to great effect 40-years ago by Antony Hewish in the design of the telescope with which pulsars were discovered.

Paul Alexander

Fig. 1: The Arc-minute MicroKelvin Imager (AMI) at the Cavendish’s Lord’s Bridge Radio Observatory. The nine precision antennae search for holes in the Cosmic Microwave Background Radiation at a frequency of 16 GHz.

Fig. 2: The reconfigured Ryle telescope in compact configuration.

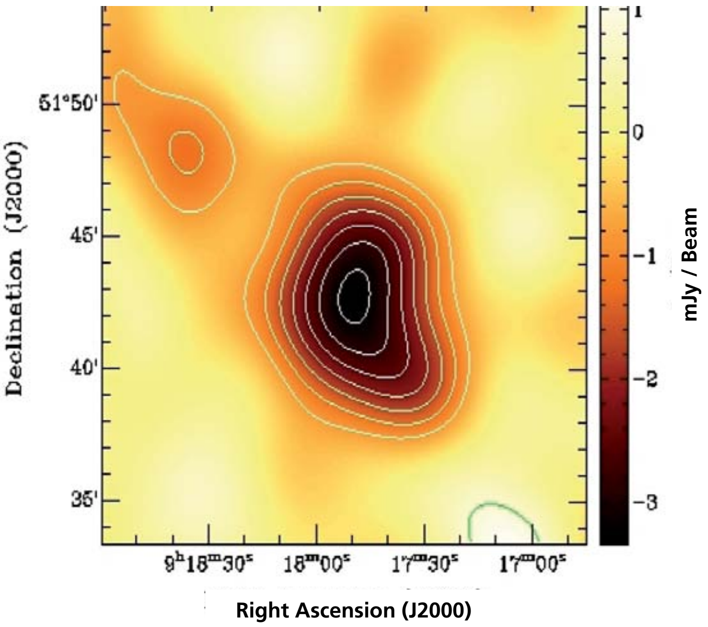


Fig. 3: An image of the ‘hole’ in the CMBR in the direction of the cluster of galaxies Abell 773, as observed by AMI. The Ryle telescope was used to remove the contribution of point radio sources.

Fig. 4: Members of the ALMA Commissioning and Science Verification Review Meeting and attendees assembled in front of an antenna transporter and a MELCO and a VERTEX antenna outside the Base Facility building. The transporter takes the antennae from 3000 m to the Chajnantor plateau at 5000 m. Richard Hills is in the centre of the front row. © ALMA (ESO/NAOJ/NRAO).

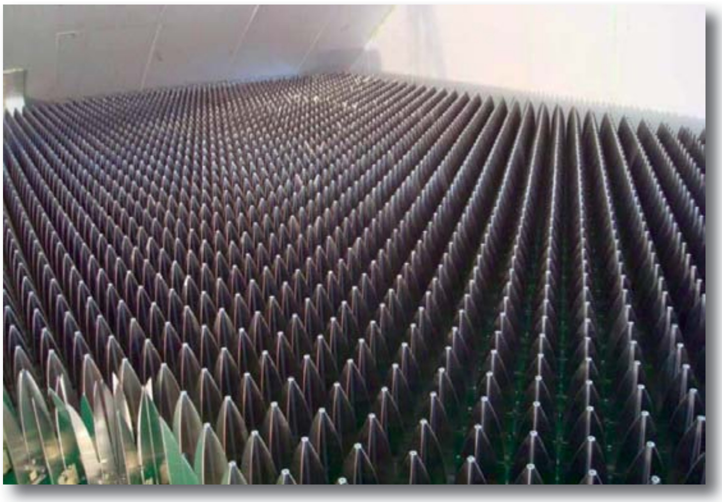


Fig. 5: An example of an aperture array developed as part of the preparatory studies for the SKA project. The picture shows the aperature arrays forming a contiguous static array which can be pointed electronically (courtesy of the SKADS consortium).

Dr Gordon Squires (1924–2010)

With sadness, we report the death of Gordon Squires who passed away peacefully on Saturday 10th April 2010 in Cambridge. Gordon was one of the pioneers of neutron scattering in the postwar period, writing the standard textbook on the subject, *Introduction to the Theory of Thermal Neutron Scattering*. He made a number of original scientific contributions to this field, including measurements of the ortho- and para-hydrogen cross-sections with A. T Stewart in 1953, the first observation of critical scattering with neutrons (1954), and a series of studies of the lattice dynamics of elements with his students.

In 1942 Gordon arrived in Cambridge for the first two years of his undergraduate studies. These were interrupted by his military service, which was spent carrying out research at the Royal Aircraft Establishment. After the War, he returned to Cambridge to complete Part II Physics followed by PhD research with J. M Cassels, using a cyclotron-driven neutron source. After his PhD he worked on the first British Reactor BEPO in Harwell, and then spent two years in the USA, first at Princeton University and then in Enrico Fermi's lab in Chicago where sadly Fermi died before Gordon arrived. He ended up at MIT, before moving back to Trinity College Cambridge and the Cavendish Laboratory in 1956, where he remained ever since. The Squires group soon established itself at Harwell, long before any formal user programme was established, sharing a time-of-flight beam line with Peter Egelstaff's group, originally on the world's first liquid hydrogen cold source at the BEPO reactor and later on the cold source at the DIDO reactor.

What many of us will remember most vividly was Gordon's outstanding qualities as a research supervisor and a gifted university teacher in the years that followed. As a university lecturer and Director of Studies for many years at Trinity College he oversaw the education of many generations of undergraduates in physics, writing a highly successful book, *Practical Physics*, for use in undergraduate laboratory courses. A particular passion of his was the teaching of quantum mechanics through tutorials and lectures that quickly became renowned as models of clarity and elegance in university teaching. His undergraduate text *Problems in Quantum Mechanics with Solutions* and an article on quantum mechanics for the *Encyclopaedia Britannica* also ensured that a wider audience was able to enjoy his skill in conveying the physics behind this non-intuitive subject.

Following his retirement, Gordon took on the role of curator of the Cavendish Collection of historically important scientific instruments within the Cavendish Laboratory, looking after and displaying its unique collection of artefacts. The equipment includes the apparatus used by James Chadwick to demonstrate the existence of the neutron. His lectures on historical topics were quite outstanding in the rigour with which he expounded the routes to many of the great discoveries in physics. Right up to the months before his death, he continued to develop exhibits for the museum and show visiting groups the riches of the collection. In his last days he finished writing a book chapter on the Physicists of Trinity College, starting with Newton, followed by the first five Cavendish Professors of Experimental Physics - Maxwell, Rayleigh, J.J Thomson, Rutherford, and L Bragg.

We pass on our deepest sympathy to his wife Shoshana and two sons, Adam and Dan.

Malcolm Longair, with acknowledgements for the assistance of the Squires family and for permission to quote from an obituary written by Andrew Boothroyd, Robert Robinson and their colleagues from the neutron scattering community.

The Quantum Mechanics of Biological Molecules

Your recollections of quantum mechanics may be of a theory that could qualitatively explain many phenomena but which only provided exact quantitative results for a very small number of systems, generally those containing a single particle. It may therefore come as a surprise to learn that quantum mechanical calculations are now routinely carried out to predict accurately the physical and chemical properties of systems containing many hundreds of atoms. These calculations can predict properties such as bond-lengths, phonon frequencies, elastic constants, reaction and activation energies of chemical reactions, optical properties, nuclear magnetic resonance (NMR) spectra and many others. Such computations are usually referred to as *first principles* or *ab initio* quantum mechanical calculations.

The reason for this revolution in our ability to solve the equations of quantum mechanics is a combination of many theoretical, numerical and algorithmic advances and, particularly, the availability of supercomputers. Remarkably, detailed analysis shows that innovations in the way in which the calculations are carried out have produced a factor 100 increase in performance for every factor of 10 increase in the speed of computers. This rule has been found to be the case in many branches of computational science and it emphasises the importance of innovation in all aspects of software engineering rather than simply relying on the availability of ever more powerful computers. The Theory of Condensed Matter Group (TCM) in the Cavendish has been at the forefront of the development of software packages for such first principles calculations for more than 30 years.

One of the codes we have developed is called CASTEP [1]. This code is used by many academic researchers in the UK and has been sold commercially by Accelrys [2] since 1994. Annual sales have exceeded £1 million every year since 1998 and cumulative sales now exceed $25 million. A list of some of the papers that contain the results of CASTEP calculations can be found on the Accelrys website [3]. Some examples of first principles simulations, such as the catalytic reaction of methanol in a zeolite, surface diffusion and melting of aluminium and the oxidation of aluminium and silicon, are available on the TCM website [4] and you are very welcome to download these.

The application of first principles calculations to biological systems began about 15 years ago. Our early results were encouraging but they made it very clear that existing methods were too computationally expensive to be applied routinely to such problems. The reason is that the computational cost of conventional first principles calculations using codes such as CASTEP increases as the cube of the number of atoms in the system. To overcome this obstacle, members of the TCM Group developed another first principles code, ONETEP [5], which provides the same state of the art accuracy as CASTEP but with a computational cost which scales linearly with the number of atoms in the system. ONETEP allows first principles calculations to be performed for systems containing many thousands of atoms, such as proteins, on quite modest supercomputers.

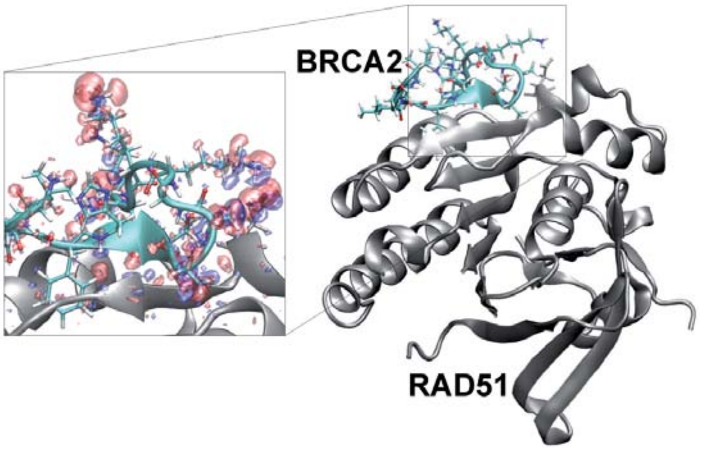


Fig. 1: The 3000 atom protein-protein interface between BRCA2 and RAD51. (inset) Electron transfer between the two proteins upon binding as calculated by ONETEP.

One such system is the protein-protein interface between RAD51 and BRCA2 (Fig. 1), which is being investigated in collaboration with the Cambridge Molecular Therapeutics Programme [6]. BRCA2 is responsible for binding to and delivering RAD51 to sites where DNA molecules have been damaged. RAD51 mediates the error-free repair of breaks in the double-stranded DNA helix. The importance of this process is that mutations in BRCA2 have been shown to lead to a predisposition to breast cancer, and so, an accurate picture of the interactions between the two proteins is of great importance. Crucially, interactions on the scale of protein-protein interfaces are governed by the laws of quantum mechanics and we may therefore use ONETEP to calculate very accurate binding energies for single configurations of the proteins.

Yet the dynamical nature of biological systems means that such an approach rarely tells the whole story. In fact, the typical time scales over which protein-protein interactions fluctuate, even in this relatively small system, are still beyond the scope of first principles approaches. We have therefore developed a technique in which classical molecular dynamics, a 'ball and spring' model, is used to simulate the dynamical behaviour of the interface. The resulting trajectory is sampled using ONETEP to calculate the average binding energy between the two proteins. With the high accuracy afforded by ab initio simulation, we aim to be able to differentiate between the binding affinities of proteins that contain rather subtle sequence mutations.

Part of the beauty of first principles simulations is its transferability to a wide range of problems about which we have relatively little prior knowledge. In collaboration with Julian Huppert of the Biological and Soft Systems Sector [7], we are studying regions of DNA molecules called *G-quadruplexes* which form four-stranded structures, instead of the more familiar double-stranded helices (Fig. 2). G-quadruplexes are found in significant regions of the human genome and are potentially important drug targets, yet the structures they adopt under physiological conditions remain uncertain [8]. We have shown that both electronic polarisation, which is well described by first principles simulation, and long time-scale dynamics, which may be accessed by classical molecular dynamics, are important factors in determining the stability of potential structures. We may therefore rank a range of experimentally-determined candidate structures by their relative energetic stabilities. Furthermore, access to the electronic structure of the whole molecule allows us to measure quantities such as circular dichroism spectra, which are expected to depend strongly on the structure of the quadruplex.

Current development work in the TCM Group aims to extend further the range of applicability and improve the accuracy of our simulations. By introducing solvent models we can represent better the electrostatic environment of realistic biomolecules. Excited state properties allow access to optical spectra and improving the descriptions of correlations between electrons allows us to model transition metal ions which are crucial to the function of many biological systems. Finally, to extend the time scales over which we can explore the behaviour of proteins we are investigating the use of rigidified models, which suggest possible large scale collective motions such as the millisecond opening mechanism of ion channel proteins in the cell membrane.

The key message of these advances is that quantum mechanics is not just about single particles but will play a central role in understanding the properties and functions of huge biological molecules. Our aim is to make it possible for any researcher to apply first principles simulations to problems in biology and medicine for the benefit of society at large.

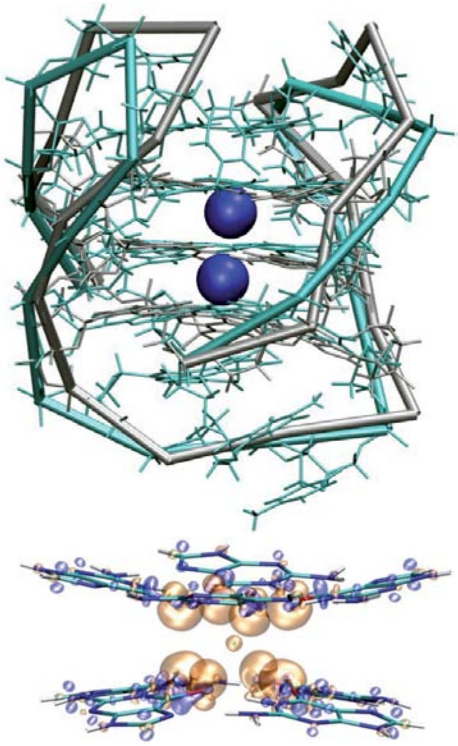


Fig. 2: (top) Snapshot of a G-quadruplex structure with metal ions (blue) running down the central channel. The original crystal structure is superposed in silver. (bottom) Electron transfer to a central K+ ion in a small region of the quadruplex.

Daniel Cole and Michael Payne

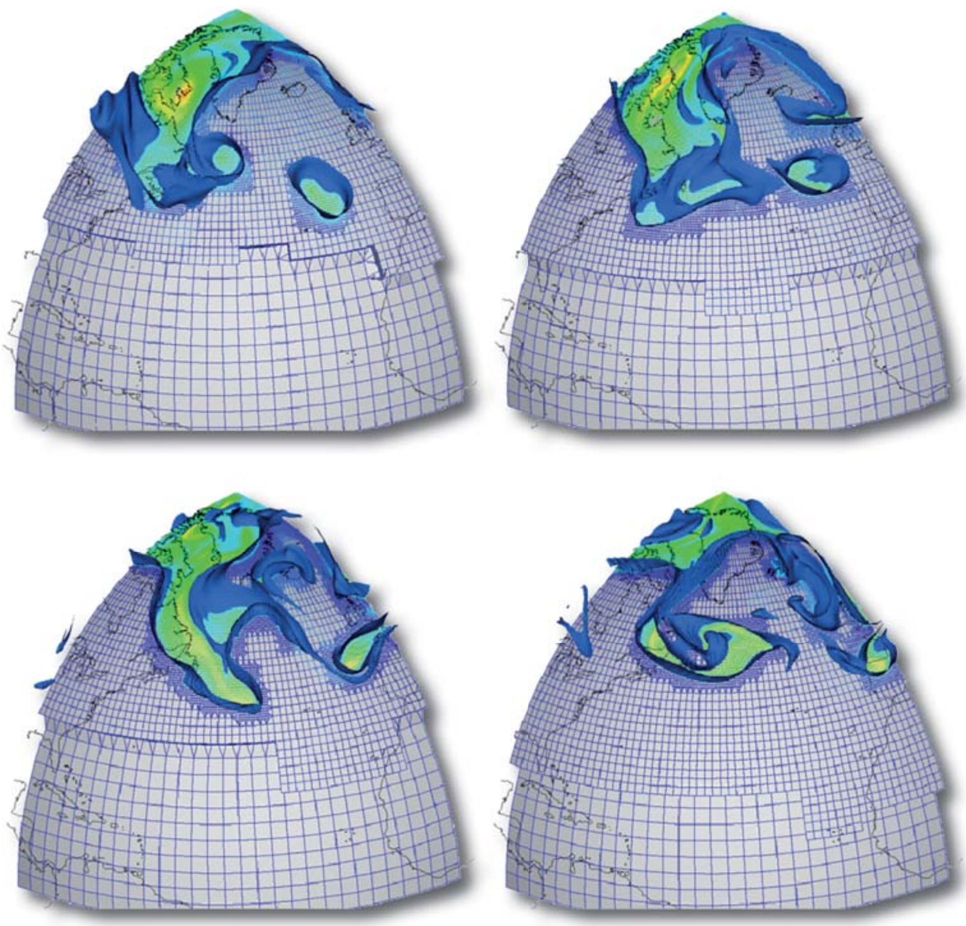
Web-page references

www.castep.org [1]
http://accelrys.com [2]
http://accelrys.com/products/materials-studio/publication-references/castep-references/index.html [3]
www.tcm.phy.cam.ac.uk/simulations [4]
www.onetep.org [5]
www.cmtp.cam.ac.uk [6]
www.bss.phy.cam.ac.uk [7]

For more details of Julian Huppert's research, see also the first edition of CavMag (February 2009, page 4). [8]

New Master's Degree in Scientific Computing

Advanced computation will undoubtedly become an essential element of every branch of science and technology over the next decade, driven by the vast amount of experimental data requiring analysis, and the need for increasingly realistic simulations of ever more complex systems. Computational science is now perceived as a core skill that is crucial in the construction of theories and models at a new conceptual level. There is a high demand for computer-literate science graduates across all areas of industry, including particularly the life sciences, technology and engineering, but the numbers of suitably-trained students cannot meet the demand.



A dynamic new initiative, the University's **Centre for Scientific Computing**, is an ambitious response to the growing demand to develop more quantitative approaches to scientific research. Cambridge offers enormous scope for extending the benefits of computation across the whole of science and technology. The co-location of many world-leading researchers in almost every area of science, combined with outstanding computational facilities, encourages and widens the interdisciplinary collaboration for which the University is renowned. The Centre is a virtual entity which incorporates the e-Science Centre, the High Performance Computing Facility and Academic Programmes.

To cater for these training needs in Scientific Computing, the Centre's new **MPhil programme in Scientific Computing**, which will take its first cohort of students in Michaelmas 2010, is offered by the University of Cambridge as a full-time course and introduces students to research skills and specialist knowledge. Covering topics of high-performance scientific computing and advanced numerical methods and techniques, it will produce graduates with rigorous research and analytical skills, who will be formidably well-equipped to proceed to doctoral research or directly into employment in industry. This bespoke course is fully flexible in allowing each student to liaise with their academic or industrial supervisor to choose a study area of mutual interest. The MPhil course is a 12-month full-time Master's Degree, which has a taught and research element. Members of the **Laboratory for Scientific Computing** in the Cavendish provide core support for the MPhil.

The taught element comprises core lecture courses on topics in scientific computing as well as elective lecture courses relevant to the science or technology topic of the research project. The core courses, which are taught during the Michaelmas Term, are on topics of high performance scientific computing and advanced numerical methods and techniques. Their purpose is to provide students with the essential background knowledge for completing their theses and for their general education in scientific computing. Students are introduced to the simulation science pipeline of problem identification, modelling, simulation and evaluation, all from the perspective of employing high-performance computing. Numerical discretisation of mathematical models is a priority, with a specific emphasis on understanding the trade-offs in terms of modelling time, pre-processing time, computational time, and post-processing time that must be made when solving realistic science and engineering problems. Understanding and working with computational methods and parallel computing is a high priority.

Appropriate elective courses are selected from Master's-level courses offered by the Departments of the School of Physical Sciences. The choice of courses will be such as to provide the students with essential background knowledge for completing their theses and for their general education in the science/technology applications of the project. The research element is a project on a science or technology topic which is studied by means of scientific computation. The topic of the project should fall within the research interests of the Departments within the School of Physical Sciences.

We look forward to welcoming our first intake of students in October 2010.

Nikos Nikiforakis

Centre for Scientific Computing Website:
www.csc.cam.ac.uk

MPhil Website:
www.csc.cam.ac.uk/academic/mphil/index.shtml

The Laboratory for Scientific Computing Website:
www.lsc.phy.cam.ac.uk/index.shtml

The figures (above) show a representative example of calculations of stratosphere-troposphere exchange, where the technique captures explicitly a number of essentially three-dimensional features such as filaments and tubes in the tropopause region during a stratosphere-troposphere exchange event that took place over the North Atlantic during June 1996. These integrations use a chemistry and transport model forced by meteorological analyses and were carried out by members of the Laboratory for Scientific Computing.

20^{th} Anniversary of the Hitachi Cambridge Laboratory and the 100^{th} Anniversary of Hitachi Ltd

On Wednesday 5th May 2010, a special 5th Hitachi Cambridge Seminar was held to mark the 20th Anniversary of the Hitachi Cambridge Laboratory and the 100th Anniversary of Hitachi Ltd. The University of Cambridge and Hitachi Limited began collaborative research in 1989 when the Hitachi Cambridge Laboratory (HCL) was established at the Cavendish Laboratory with the aim of using nanostructure physics to create new concepts for advanced electronic and optoelectronic devices. At that time, quantum effects were becoming important in the behaviour of conventional electronic devices, and the HCL was given the remit of developing new devices from a quantum mechanical viewpoint.

The collaboration has been and continues to be profitable for both parties with the HCL offering advanced measurement and characterization techniques that expand the experimental research capability in the Cavendish Laboratory, while the University, through collaborative projects, makes state-of-the-art micro- and nano-devices accessible to Hitachi researchers. The Hitachi Cambridge Laboratory shares its facilities with the Microelectronics Research Centre and promotes joint workshops and research programmes with many research groups in the Department of Physics. The HCL building was expanded in 1995, and now houses the HCL, the Microelectronics Group and part of the Cavendish Optoelectronics group.

One of the main early research fields was single-electronics, notable successes being the development of the first single-electron memory in 1993 and the first single-electron logic devices in 1995. These led to PLEDM memory technology, and also to many aspects of the present research areas. Some examples of research in the HCL include:

- *Nanospintronics* offers opportunities for a new generation of devices combining standard microelectronics with spin-dependent effects. Hitachi is one of the largest manufacturers of hard disc devices for information storage, and the HCL is part of a global collaboration within Hitachi, aimed at developing new spintronic devices for future hard disc and low-power electronics applications.

- The history of *spintronic devices*, used already in computer hard drive read heads and magnetic random access memories, is reminiscent of that of conventional microelectronics. It started about 20 years ago with a simple 'spintronic wire' - an Anisotropic Magneto-Resistance (AMR) sensor, followed by more elaborate diode-like spin-valve elements based on the Giant MagnetoResistance (GMR) or the Tunnelling MagnetoResistance (TMR) effects. GMR and TMR also opened new paths to design magnetic random access memory (MRAM) devices. New exciting possibilities are offered by ferromagnetic semiconductor devices that can realise the full potential of spintronics, as they integrate the magnetic and semiconducting properties of materials allowing the combination of information processing and storage functionalities.

- Another new type of spintronic device involves *non-magnetic semiconductors*, in which the spin coherence length can be relatively long. Moreover, nonmagnetic semiconductors, such as III-V heterostructures, offer an unprecedented means for electrical detection and manipulation of spins via spin-orbit coupling. As a source of spin polarised electrons, one may use spin-injection from ferromagnetic metals that have sufficiently high Curie temperature. However, electric field generated spin polarisation may also be envisioned using spin-orbit coupling related phenomena, such as the recently discovered spin Hall effect.

- *Quantum Information Processing* (QIP) is a new information science based on the principles of quantum mechanics, and spans quantum computing and quantum cryptography. The HCL is actively building these sciences into a new information technology, investigating a wide range of approaches to making devices that can be used to build solid-state quantum computers and quantum cryptography systems. The first active field has been quantum information processing in which the classical 'bits' that store information are replaced by 'quantum bits' or 'qubits'. Examples of the use of such quantum processing techniques are the factorising of large integers for cryptographic applications, fast searching in large databases along with simulation and modeling of quantum systems. The technology to produce such systems is not yet available. Research at the HCL focuses on experimental and theoretical studies of charge states in silicon isolated double quantum dots, radio-frequency single electron transistors as well as quantum key distribution.

- In collaboration with the Hitachi Professor of Electron Device Physics, Henning Sirringhaus, the HCL is investigating the properties of organic electronic devices. Organic electronics is of enormous technological interest for its ability to integrate circuits, batteries, sensors, and other functionalities on flexible plastic substrates using solution and printing processes at room temperature. Recently organic displays incorporating organic light-emitting diodes reached the marketplace. The Hitachi Group is moving rapidly ahead with R&D on organic TFTs organic actuators, and other organic devices, and has already verified the operation of prototype devices built using solution-processed materials, anticipating the growing use of solution and printing-based processing.

David Williams, Director of the Hitachi Cambridge Laboratory

Fig. 1: Members of the Hitachi Cambridge Laboratory in 2010. David Williams is second from the left in the front row and Henning Sirringhaus on the far right in the front row.

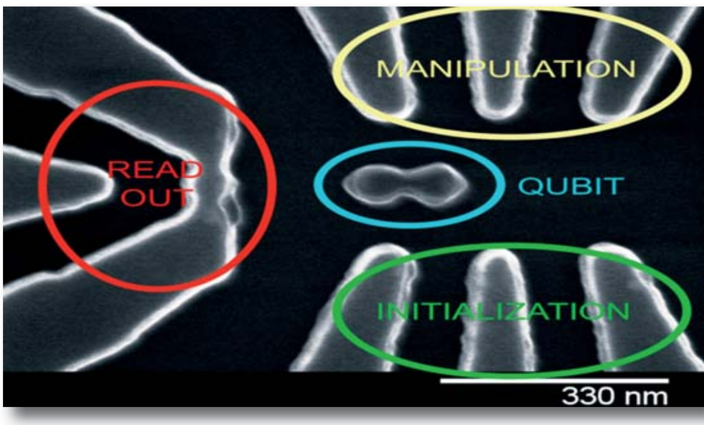


Fig 2: A qbit nano-device constructed in the HCL.

The Mechanical Workshops Yesterday, Today and Tomorrow

Excellence in experimental research demands excellent support facilities and the Cavendish has been fortunate to employ assistant technical staff of the very highest order throughout its history. A splendid example is the team of assistants who supported JJ Thomson in his discovery of the electron in 1897. Pride of place must go to Ebenezer Everett who worked with Thomson through the heroic period when the omnipresent role of the electron in physics was established (Fig. 1).

Fig. 1: The Laboratory assistants in December 1900. Ebenezar Everett is on the right in the front row.

Thomson was wholly dependent upon the skill of Everett in the construction of his equipment. In a delightful story told in Robin Strutt's biography of JJ Thomson, a powerful electromagnet surrounding a discharge tube was to be switched on. In Strutt's words,

"The conversation went as follows:

JJ: 'Put the magnet on.' There followed a click as Everett closed the large switch.
JJ: 'Put the magnet on.'
Everett: 'It is on.'
JJ: (eye still to the microscope) 'No, it isn't on. Put it on.'
Everett: 'It is on.'

A moment later JJ called for a compass needle. Everett ... returned with a large needle 10 inches long. ... JJ took it, and approached the electromagnet. When about a foot away the needle was so strongly attracted to the electromagnet that it swung round and flew off its pivot, crashing into the bulb (which burst with a loud report) and coming to rest between the poles of the magnet. ... Everett was glowing with triumph, and JJ looking at the wreck with an air of dejection. 'Hm,' he said. 'It was on.'"

Thomson wrote Everett's obituary stating: 'Everett took a very active and important part in the researches carried on in the Laboratory, by students as well as by the professor. The great majority of these involved difficult glass blowing, which was nearly all done by Everett ... He made all the apparatus used in my experiments for the more than 40 years in which he acted as my assistant.'

Today, the same level of attainment and dedication characterises the work of the assistant staff in the mechanical workshops that have been dramatically enhanced over the last two years in response to the increasingly complex requirements of research. Following the retirements of Terry Stubbings and Dave Johnson, Peter Norman was appointed as Head of Mechanical Engineering Services, bringing together the work of the former Mott and Main Workshops. This appointment was just one element of a broad-ranging review carried out by Bill Allison, Richard Phillips, Peter Bystricky and David Peet. As the images show, the main workshop has been extensively refurbished and new offices provided, an investment of £350k (Fig. 2). This has given additional capacity in Computer Aided Design and has also helped to bring staff together.

Fig. 2: The new mechanical workshops with state-of-the-art CNC machines.

Six new CNC mills and lathes have been procured and staff have undergone extensive training in their use. The establishment of new Groups such as the Atomic Mesoscopic and Optical Physics Group has led to increased demands for high-tolerance work and the new equipment greatly helps in this area. The last few months have also seen a considerable increase in activity in the former Mott Workshop, including the provision of a new Student Workshop under the leadership of Nigel Palfrey (Fig. 3). The training of postgraduate students in workshop practice is seen as a key element of their programme. With a clear grounding in workshop practice they can appreciate the potential for innovation, the skilled support that is available to them and the need to work collaboratively towards an effective solution to their project.

Fig. 3: The new students' mechanical workshop.

New equipment and spaces to work in are far from the full picture. As experienced staff have retired, it has proved a challenge to recruit people with all the attributes needed to support such an extensive research programme. The Laboratory has been extremely fortunate in its recent appointments in the workshops and the future is looking very promising. The staff continue to develop the long Cavendish tradition of close involvement and interaction between technician and academic in the design and delivery of new items.

The Department has led the way in the University in developing an Apprenticeship Training Programme for those seeking to follow a career in mechanical engineering. After winning prizes in the first years of his college course, Adam Brown, our first apprentice, has just been appointed to a permanent post in the Laboratory and will proceed to further training in October. There are other people in the pipeline and the Department has received support

Peter Norman

from the School of the Physical Science to continue this programme.

As Peter Norman remarks:

'We are continually striving to improve the service to the research within the Cavendish. With the refurbishments in the workshops we have created an improved working environment for the technicians. The addition of the CNC's and documentation in the form of ACAD drawings and production records will give future benefit in throughput, costing and traceability of previous projects and designs. We are already seeing an increased capacity and hopefully shorter lead times. Previously sub-contracted parts are now being produced in the Cavendish workshops, due to the investment in the CNC equipment and expertise from training. The future planned equipment will also provide further improvements to the service.'

Peter Norman and David Peet

Gavin Ross working on the design of the solar cell sealing press.

The completed sealing press, entirely produced in-house using the new CNC facilities.

An example of the type of project undertaken using the complete range of the services is that of a piece of equipment for the BSS Group, a 'Solar Cell Sealing Press'. The concept of the equipment was discussed between the technician and the research group. The technician then produced an ACAD design in a 3D model view that could be viewed and fine tuned to the researchers' satisfaction, prior to cutting metal. Detail manufacture drawings were produced and the parts manufactured on both CNC and conventional machines. The equipment was assembled and completed with the electronic controls as shown in the picture.

Toshiba Admitted to the Guild of Cambridge Benefactors

Admission to the *Guild of Cambridge Benefactors* recognises the substantial contributions that Toshiba has made to research activities within the University over the past 19 years. In 1991 Toshiba founded a research laboratory on the Cambridge Science Park under the direction of Michael Pepper, formerly Head of the Semiconductor Physics group at the Cavendish Laboratory. A major aim of this research centre was to develop novel semiconductor devices that directly exploited the laws of quantum mechanics for their operation, in collaboration with researchers at the Cavendish.

This research cooperation, now led by David Ritchie, Head of the Semiconductor Physics Group, and Andrew Shields of Toshiba Research Europe, has been highly successful with over 200 published papers, a number of them in high-impact journals such as *Science*, *Nature* and *Physical Review Letters*. Novel electronic and opto-electronic devices have been fabricated in the Semiconductor Physics group and these are characterised at the Toshiba laboratory using state-of-the-art optical and electrical measurement systems.

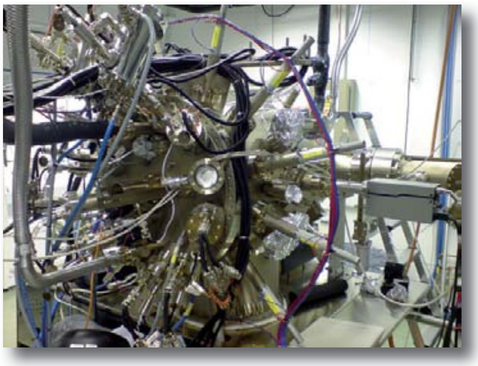


Fig. 1: A molecular beam epitaxy (MBE) system for the growth of ultra-pure III-V semiconductors.

To fabricate these devices, molecular beam epitaxy (MBE) has been used to grow crystals of extreme purity (1 part in 10^9) in group III-V semiconductors such as gallium arsenide (GaAs) and aluminium gallium arsenide (AlGaAs) with control close to the level of a single atomic layer (Fig. 1). These semiconductors are processed into device structures using a range of techniques to etch small patterns as well as deposit patterns of metal on the surface to form electrical contacts and gates. Many PhD students involved in this collaboration have fabricated their samples at the Cavendish and then used the measurement systems at the Toshiba research laboratory.

A major theme of this research over the past few years has been the development of devices for the processing of quantum information. The control and manipulation of individual quantum objects (or qubits) - such as electrons or photons - and their interaction with other quantum objects is the subject of considerable current research interest worldwide. Potential applications for these technologies include a powerful new form of "quantum" computer, ultra-secure communications and high resolution imaging systems.

The collaboration between Semiconductor Physics and Toshiba Research Europe has recently developed devices that produce a stream of single photons. This is achieved by embedding a nano-scale "self-assembled" quantum dot made of indium antimonide (InAs) in a slab of GaAs semiconductor, itself placed between regions of p and n-type

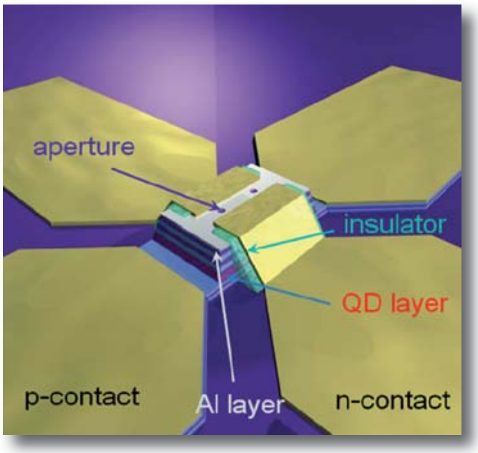


Fig. 2: A schematic of a single or entangled photon light emitting pn diode.

GaAs (Fig. 2). If pulses of current are then passed through this device, electrons and holes recombine in the quantum dot to produce a stream of single photons of very well defined wavelength. Toshiba Research Europe has incorporated one of these single-photon sources into a quantum key distribution system where a cryptographic key is distributed over many kilometres of optical fibre using a stream of single photons.

Recent experiments have tuned the wavelength of the photons emitted by two different devices to be the same and these photons have been shown to be quantum mechanically indistinguishable, an important result recently published in *Nature Photonics*, which implies that it should be possible to transfer a quantum state from one dot to another.

A similar device developed by the collaboration is a source of pairs of photons that are quantum mechanically entangled.

The InAs quantum dots used in the single-photon sources described above can, under certain circumstances, be made to emit two photons one after the other where the polarisations of the two photons are linked in an entangled quantum state. This means that if you measure the polarisation state of one photon you can affect the state of the other some distance away, a concept that upset Albert Einstein considerably when it was first mooted, declaring it to be "*spukhafte Fernwirkung*" or "*spooky action at a distance*". This type of device was first demonstrated in 2006 in an experiment in which a pulsed laser was used to provide the electrons and holes. By improving the understanding of the physics behind the operation of these devices, they have advanced to the stage where they can now be used in quantum information experiments.

Most recently an entangled light emitting diode has been developed and was reported in a Letter to *Nature* on June 3rd 2010 (Fig. 3). This work demonstrates that a light source of this type can be made in a very compact form, although it relies on being operated at low temperatures. This device has many applications, in quantum communications as a repeater to transfer quantum states over greater distances than are currently possible, as a key element in a quantum computer, as part of a teleportation system for quantum states and for improved resolution in optical imaging and storage systems.

David Ritchie

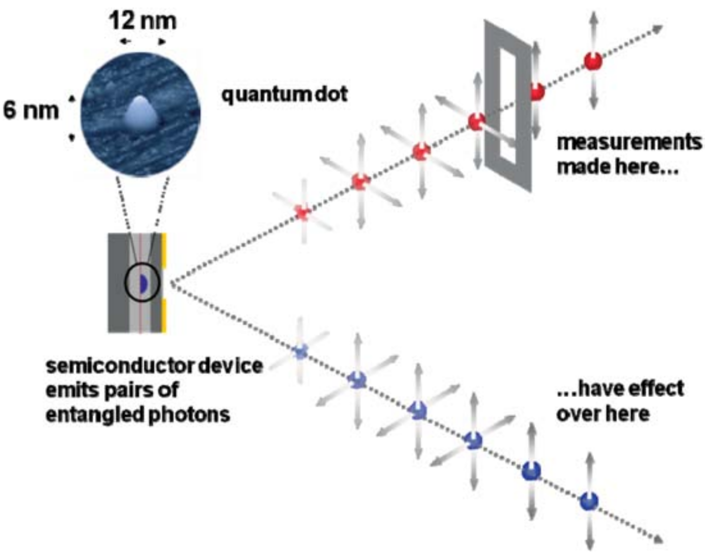


Fig. 3: An illustration of the emission of pairs of polarisation-entangled photons from a quantum dot.

Career Destinations of Cambridge Physics Alumni

We were most gratified by the positive response of Cavendish Physics Alumni to the questionnaire which we circulated with the Cavendish Laboratory 2008 booklet. This has turned out to be a very helpful exercise and has given a panorama of the career destinations of alumni. Just as in the case of astronomical databases with which I am familiar, the data are dominated by selection effects, which can strongly influence the conclusions drawn.

Thanks to the information provided by alumni in response to Cavendish questionnaire, we have been able to develop a much more revealing picture of the career destinations of alumni. There are 1116 alumni who responded to the questionnaire of whom 904 gave details of present or past employment, a large fraction of the remaining 212 being retired. I went through all the responses of alumni and made assignments to the employment categories defined by CUDO.

To begin with, we analysed statistically the 904 alumni for whom assignments had been made. These raw data produced the remarkable result that a large percentage of alumni remained in the academic or research sector (Fig. 1). It was immediately apparent that this was a significant overestimate because very often the data referred to the occupation immediately upon graduation. On many occasions, graduates would opt for further training, or take up fellowships or other forms of non-tenured appointment in the academic sector.

One of our objectives was to find out how Cavendish alumni contribute to the economy of the UK and so we further restricted the analysis to those who gave the UK as their designated country of employment. Then we restricted the analysis of final career destinations to those who had matriculated between 1960 and 1995 inclusive. The intention of this restriction was to exclude most retired alumni and also those who went on to further academic training or post-graduate work after matriculation. These data should provide a better representation of the 'final' employment destinations of alumni. The resulting histogram is shown in Fig. 2. There are still peaks at Education and Training and Research and Development, but there is also a very wide spread of careers. Particularly notable are the large numbers in business-general, finance, healthcare, information technology and natural resources and utilities. In addition, a number of graduates find careers as school teachers. The overall conclusion is that, in their final career destinations, about 25% of physics alumni remain within the university or research sector, while 75% find employment in areas of the greatest importance for society. It was very pleasing to observe how many alumni are now CEOs of companies.

Another measure of the impact of Cavendish alumni upon UK academic life is an analysis of over 2000 physicists and astronomers who were submitted to the UK Government's 2008 Research Assessment Exercise (RAE). Perhaps the most interesting statistics are the numbers of full professors in the UK who graduated in Physics at Cambridge. For inclusion in these numbers, the persons must have matriculated in Physics or Astronomy either as an undergraduate or graduate – those who matriculated in DAMTP and other cognate departments are excluded. We also excluded those who only came to Physics and Astronomy as post-docs. Fig. 3 shows that Cambridge graduates have had a very large impact upon the UK academic sector, providing many of those who now lead UK University research and teaching.

These statistics are very helpful in providing us with reasonably objective figures about the impact of Cavendish graduates upon UK society and academic life. There are, of course, incompletenesses in any exercise of this type, but the overall picture serves to confirm our view that we are making a large contribution to society at large. We greatly welcome your continued interest in our goal of spreading the word about the importance of what we are doing. The information about your careers is very important to us and we will be very grateful if you can continue to keep us informed about how your career has developed.

Malcolm Longair

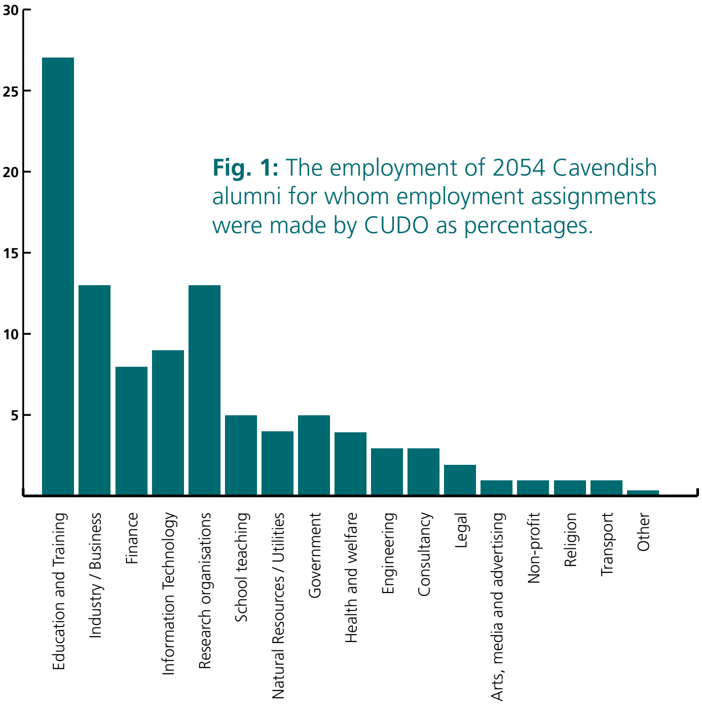


Fig. 1: The employment of 2054 Cavendish alumni for whom employment assignments were made by CUDO as percentages.

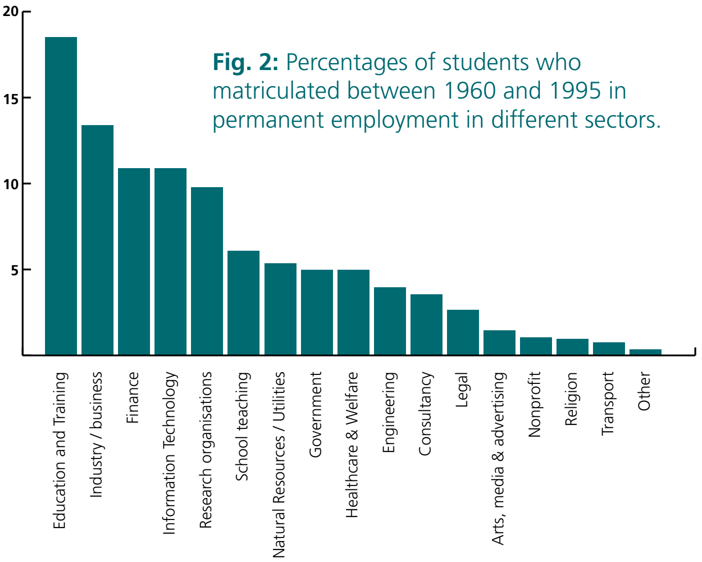


Fig. 2: Percentages of students who matriculated between 1960 and 1995 in permanent employment in different sectors.

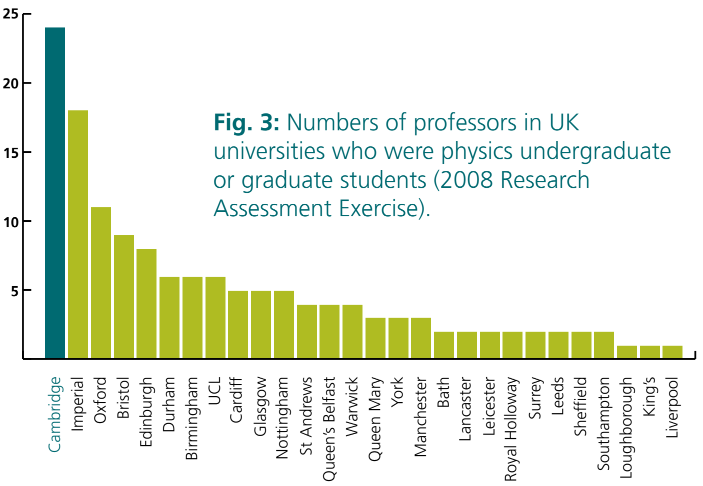


Fig. 3: Numbers of professors in UK universities who were physics undergraduate or graduate students (2008 Research Assessment Exercise).

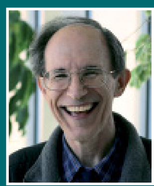
Cavendish News

Warmest congratulations to ***Athene Donald*** on her appointment as a Dame Commander of the Order of the British Empire (DBE) for services to Physics in The Queen's Birthday Honours. She has also won the Science and Technology award issued by the women's lifestyle publication, *Glamour Magazine,* and the Faraday Medal of the Institute of Physics for her many highly original studies of polymers.

Cavendish Professor ***Richard Friend*** was a laureate of the International Millennium Technology Prize awarded in Helsinki.

We are delighted to announce the promotions of ***Paul Alexander*** of the Astrophysics Group to a Professorship, ***John Ellis*** of the Surface, Microstructure and Fracture Group to a Readership and ***Chris Lester*** of the High Energy Physics Group to a Senior Lecturership.

Congratulations to RCUK Fellow ***Julian Huppert*** on being elected Liberal Democrat member of parliament for Cambridge.

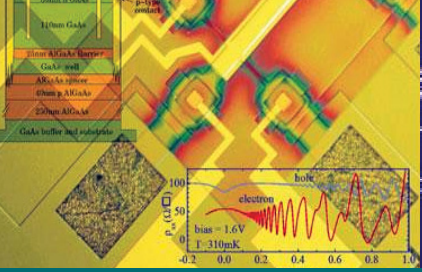
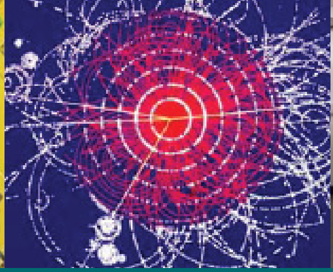


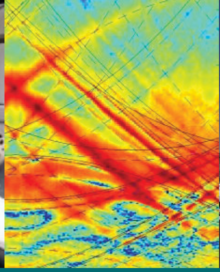
The Royal Society have awarded ***Gil Lonzarich*** its Rumford Medal for his outstanding work into novel types of quantum matter using innovative instrumentation and techniques.

We are delighted to announce the election to Fellowship of the Royal Society of ***Russell Cowburn*** who joined the Department from Imperial College on 1st June 2010. Russell is distinguished for his research on magnetism in nanostructures, and for the translation of his scientific discoveries into disruptive technologies. Half scientist, half technologist, he initiated the field of magnetic logic and is the inventor of the anti-counterfeiting laser-based technology Laser Surface Authentication.

Innovation Competition Prize for Cavendish Researchers

CamBridgeSens, the University of Cambridge's EPSRC funded network for sensor research, have just announced Innovation Competition grant winners of grants totaling more than £75K to benefit researchers at the University of Cambridge. Among the winners were ***Adrian Ionescu*** and ***Justin Llandro*** from the Cavendish working together with ***Nicholas Darton*** from the Department of Chemical Engineering and Biotechnology, and ***Matthias Ediger*** of the AMOP Group together with colleagues in Biochemistry and Chemical Engineering for novel non-viral vectors for molecular diagnosis and traceable drug delivery.



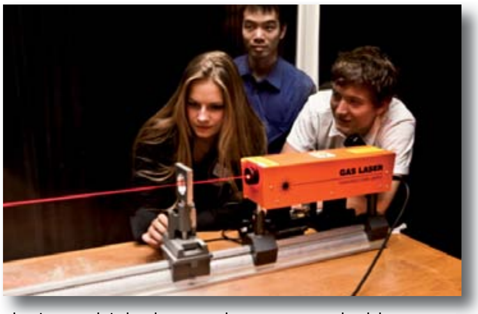

Physics for Young People: Summer & Autumn 2010

Lisa Jardine-Wright

Senior Physics Challenge:

This is the fourth year of this very successful course, which can be characterised as 'Physics with the Mathematics put back in', aimed at redressing the decline in the mathematical content of school physics. We received over 200 applications from the highest calibre Y12 (AS-level) students to participate in this initiative called the **Senior Physics Challenge**. Co-director Anson Cheung and I selected 66 students to visit Cambridge this summer from schools all over the United Kingdom.

The summer school took place over four nights from the 27th June until the 1st July,



during which the students attended lectures on kinematics and special relativity and practical laboratory classes on dynamics and optics. The aim of these four days of intensive tuition is to develop problem-solving and experimental skills and to demystify the transition from A-level, or equivalent, to university physics. The participants are hosted to dinner and accommodated in a number of participating colleges, including Christ's, Churchill, Corpus Christi, Fitzwilliam, Newnham, Pembroke, Robinson, St John's and Trinity.

Student applications are initiated by the recommendation of their teachers and any interested teacher may register for the 2011 course online and receive updates and notification of the next application round. To find out more, go to our website www-spc.phy.cam.ac.uk.

Undergraduate Open Days:

On 1st and 2nd July 2010 the Cavendish opened its doors to the next wave of potential undergraduates. These open afternoons are designed to coincide with the Cambridge University central admissions open days but are stand-alone activities to which any year twelve (AS-level or equivalent) students and their families are invited.

One of the aims of the open afternoons is to introduce potential students to the variety of experiments that they will undertake as physics undergraduates, and to provide them with an opportunity to speak with graduate demonstrators and supervisors. Julia Riley gave an example of a first-year undergraduate lecture on special relativity. A further session offered interested visitors a museum tour and talk about the history of the ground-breaking physics performed at the Cavendish Laboratory. Further information about next year's event will be provided on our website at www-outreach.phy.cam.ac.uk/uopenday.

Physics at Work 2010 – Bookings now open

Bookings for the 26th annual *Physics at Work* exhibition are now open to schools – spaces are filling fast! This unique exhibition runs for three days, this year from 21st until 23rd September, with two sessions each day, morning sessions beginning at 9am and afternoon sessions at 1pm. During each half-day session school groups visit six different exhibits selected by the organisers to include both university and industrial exhibitors, illustrating the many varied ways in which physics is used in the real world. This year there will be twenty-four exhibitors.

The exhibition is targeted at 14-16 year olds with some schools bringing their talented year 9 students and others bringing year 12 students who are considering potential careers in physics. Schools are welcome to bring as many students as they are able, provided the teacher to student ratio is about 1:5. On arrival at the Cavendish a given school party will be split into groups of approximately 15 students with 1 accompanying teacher. Map in hand each group is then led to their first exhibit to follow their own tailored route around the Cavendish.

Approximately 400 FREE places are available for each half day session and schools travel from all over London and the South East to attend this event. Teachers interested in bringing their classes to the 2010 exhibition should book online at www-outreach.phy.cam.ac.uk/physics_at_work/2010 as soon as possible to avoid disappointment.

Cavendish Laboratory Open Day for Alumni

Following the great success of last year's open day for alumni, we are delighted to invite all alumni and their guests to the 2010 Cavendish Open Day, which will take place on **Saturday 25th September 2010**. The Laboratory will be open from **2.00pm – 5.30pm** to all alumni of the University. All research areas of the laboratory will be open. Complementary refreshments will be available throughout the afternoon.

From **4.00pm – 5.00pm**, there will be a lecture in the Pippard Lecture Theatre at the Cavendish by **Peter Littlewood**, Head of the Cavendish and Professor of Theoretical Physics, and **Malcolm Longair**, Emeritus Jacksonian Professor of Natural Philosophy and Director of Development on:

The Cavendish Laboratory in 2010: The Extreme, Quantum, Material and Biological Universes

All are very welcome to attend.

Contacts

If you would like to discuss how you might contribute to the Cavendish's Development Programme, please contact either Professor Malcolm Longair (msl1000@cam.ac.uk) or Professor Peter Littlewood (HoD@phy.cam.ac.uk), who will be very pleased to talk to you confidentially. Further information about the Cavendish's Development Programme can be found at: **www.phy.cam.ac.uk/development**

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