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News from the Cavendish Laboratory

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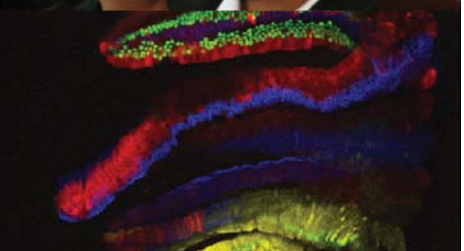

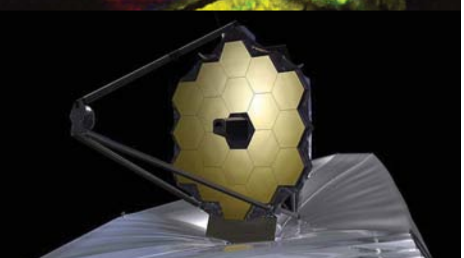

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ALMA – 'First Light'

Traditionally in astronomy, the very first image taken with a new telescope is referred to as 'First Light'. After many years of planning, development and construction, the first scheduled observations with the Atacama Large Millimetre/Submillimetre Array (ALMA) took place on 30th September 2011. ALMA is a partnership between Europe, North America and East Asia in cooperation with Chile and is located in the Atacama region in the north of Chile. Although the telescope is far from complete – these 'first light' observations used only 16 of the planned 66 antennas – this event is a very import milestone for the project (Figure 1).

The array of antennas covers an area 16km in diameter in its most extended configuration and is designed to receive signals at wavelengths in the range from 10mm to about 0.3mm (30 to 1000 GHz). Especially at the shorter end of this waveband, the signals are strongly absorbed by water vapour in the atmosphere, which is why the telescope is located in one of the driest places in the world at an altitude of 5000 metres. At the time of writing, 27 antennae have now been transported to the high site (Figure 2).

The ALMA project has strong links to the Cavendish. Firstly, as described by Paul Alexander in CavMag4, the design of ALMA is founded on the principle of Aperture Synthesis developed by Martin Ryle and his team at the Cavendish. Secondly, a key element of the system, developed by John Richer, Bojan Nikolic and colleagues in the Astrophysics Group, is the method by which the effects of fluctuations in the residual water vapour in the atmosphere are measured and corrected. Without correction, these would cause the coherence of the signals arriving at the different antennas to be lost. The solution is to install accurate and stable millimetre-wave receivers on each antenna, tuned to the emission line of water vapour at 183GHz, and to measure, every second or so, the exact amount of water along the line of sight towards the astronomical object being observed. Using software developed by the Cavendish team, a correction can then be derived for the propagation delay produced by the water vapour. Experiments to test this process have shown that it works well and is now used routinely on all the telescopes.

A third linkage is that the ALMA Project Scientist, Richard Hills, is in Chile on leave from his post as Professor of Radio

Fig. 1: (top). 22 of the ALMA antennas which were commissioned by October 2011 at the observing site at 5000 metres altitude.

Fig. 2: Antenna 16, the first European 12-metre antenna, on the transporter from the ALMA Operations Support Facility at 2900 metres to the summit plateau at 5000 metres.

Astronomy at the Cavendish. The task of bringing the telescope into operation has been very challenging but tremendously exciting, especially now that the first results are starting to appear. The 12m antennas are designed to maintain a surface accuracy of better than 25 microns at all orientations despite the extremes of temperature, solar heating and wind found at the site and have to point and track objects on the sky to an accuracy of better than a second of arc. The signals are extremely weak and for their detection ALMA uses SIS tunnel-junctions with areas of only a few microns operating at temperatures below 4K. Very carefully designed optical systems are needed to couple efficiently the millimetre-wave signals collected by the antenna into the junctions. The detection process consists of mixing the astronomical signal with that from a reference oscillator in order to convert it to a lower frequency where it can be amplified and then digitised. An optical fibre system is used to ensure that these processes are carried out coherently at all the antennas with a timing accuracy of order 10^{-14}s. Finally the signals are brought together at a central building, again using optical fibres, where large special-purpose digital systems, the correlators, measure the degree of correlation between the data streams. The data rate from each antenna is 120 Gb/s and each bit has to be compared with the corresponding bits from all the other antennas. To do this the correlator performs roughly 2×10^{17} multiply-and-add operations per second. All the equipment is remotely controlled by computer systems and the software has to bind all the pieces of hardware together and instruct them to perform the operations in the right order and at the right times so as to make meaningful astronomical observations. The software development for ALMA has required hundreds of person-years of effort.

The first sixteen telescopes were fully commissioned with receivers for the 345 GHz waveband and, appropriately, an image made of carbon monoxide molecules in the 'Antennae Galaxies', so called because of the huge tails emanating from this extreme collision between galaxies. Figure 3(a) shows the image of the molecular line emission while Fig 3(b) shows that emission superimposed upon the Hubble Space Telescope image of the colliding galaxies.

In these images the interstellar gas in the two galaxies is undergoing a dramatic collision, in which molecular gas is compressed resulting in the formation of new stars. The great merit of the ALMA images is that they show in remarkable detail the processes of star formation occurring during the collision. Heated molecular gas can be seen throughout the galaxies, but it is most strongly concentrated towards their nuclear regions. These observations provide key information about the how stars can form in galaxies and in the process fuel their central regions where supermassive black holes are lurking. Images showing a great deal more of the real complexity involved in such processes will be obtained as the rest of the system comes online over the next two years. There is still a great deal to do before ALMA can reach its full potential but the story so far is, 'No show-stoppers yet, but plenty of headaches'.

Richard Hills and Malcolm Longair

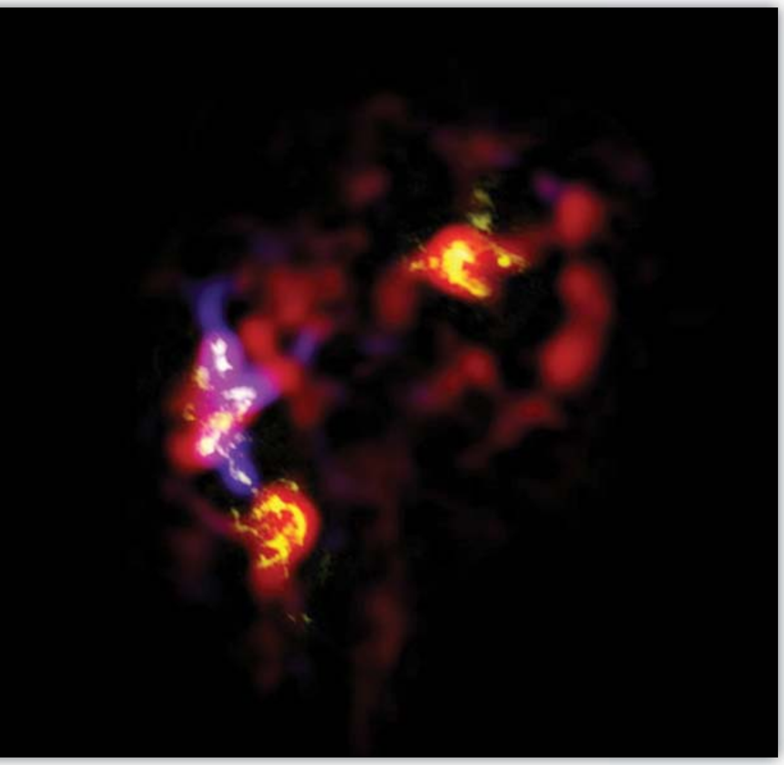

Fig. 3(a) (left): The distribution of carbon monoxide in the pair of colliding galaxies known as the Antennae.
Fig. 3(b) (right): A superposition of the carbon monoxide emission upon the Hubble Space Telescope image of the same galaxies.

Editorial

Transitions

The theme of CavMag7 is transitions, in many senses. The cover story is the transition of the international ALMA project from a technology enterprise to the 'first light' observations of astronomical objects. The molecular line image of the Antennae Galaxies is spectacular in its sensitivity and angular resolution and has been obtained with only 16 of the projected 66 antennas of the full array.

Then, there is a remarkable series of three articles by Suchitra Sebastian, Zoran Hadzibabic and Nigel Cooper on very different aspects of phase transitions in physics. Suchitra and Zoran describe very different techniques for studying phase transitions experimentally under very extreme conditions, while Nigel describes remarkable theoretical work that suggests how particles can be subjected to quite enormous magnetic fields by careful manipulation of the laser fields experienced by electrons.

The Winton programme has made the transition from a magnificent benefaction to a set of innovative research programmes with the appointments of the first six research students and two research fellows. We wish these new appointments every success in transforming our concepts of sustainability.

Finally, there is the long list of retirals and new appointments of research and support staff. In fact, transitions are everywhere in the Laboratory, as they must be if we are to maintain our position at the forefront of physics research.

Malcolm Longair

Quantum Phases of Matter Under Extreme Conditions

Condensed states of matter with long-range quantum coherence are becoming increasingly important in fundamental research and technology. For example, superconductivity has stimulated new ideas in particle physics and cosmology, and finds applications in areas such as Magnetic Resonance Imaging (MRI) and efficient energy transmission. Magnetism has provided concepts widely used in science and underpins the information revolution with the storage and fast manipulation of more and more electronic data. The new study of topological quantum order, which has evolved from the discovery of the quantum Hall effect and quantum spin liquids, is leading to the development of fault tolerant quibits for future application in quantum computers.

Our goal is to discover new or useful forms of quantum phases and to understand their nature. Central to our approach is the synthesis of a wide range of materials by various techniques, guided by our growing understanding and anticipation of diverse forms of quantum order that emerge in assemblies of strongly interacting electrons and nuclei in solids. Starting from the preparation of new materials, the discovery of novel phases is greatly boosted by the tuning of the starting, as-grown, materials via a range of techniques including chemical doping and the application of external pressure and electromagnetic fields. We have focussed on the development of such techniques in addition to those for materials synthesis and for measurements of electronic and magnetic properties under extreme experimental conditions.

We discuss below some examples of our recent materials synthesis, tuning and measurements of uncommon quantum phenomena.

High temperature superconductivity in the cuprates [1, 2]

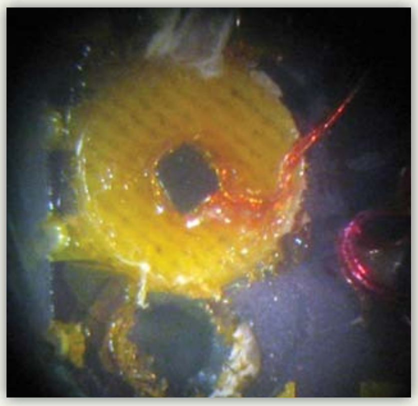

Fig. 1: A single crystal of $YBa_2Cu_3O_y$ grown by flux-growth in British Columbia. A coil is wound onto the crystal for the measurement of contactless resistivity via resonant oscillatory techniques at high magnetic fields.

The copper oxide based superconductors such as $YBa_2Cu_3O_y$ exhibit zero-resistance states at unexpectedly high temperatures, currently of the order of 135 K at ambient pressure, and are beginning to find applications in the new generation MRI magnets and in the conversion and transmission of electrical power. Despite major international efforts for over two decades, however, key aspects of these superconductors remain mysterious. Remarkably, the greatest mysteries concern the nature of the underlying state out of which superconductivity emerges in the so-called under-doped regime ($6<y<7$). We access this unconventional state in $YBa_2Cu_3O_y$ (Fig. 1) by the application of intense magnetic fields in the range 22 T to 95 T (Fig.2), high enough to suppress long-range superconducting order at low temperatures. Our measurements have found and investigated the surprising occurrence of quantum oscillatory phenomena in this regime (Fig. 3), showing conclusively that despite the strange properties of the under-doped state, it can be described at low energies in terms of excitations that satisfy the Fermi-Dirac distribution as in normal metals. The excitations do not arise, however, out of the conventional Fermi surface, but instead from a truncated Fermi surface which we find to be consistent with the existence of a special type of underlying charge density order. Our findings provide a new starting point for understanding high-temperature superconductivity in $YBa_2Cu_3O_y$.

Fig. 2: World's highest field hybrid magnet combining resistive and superconducting technologies to reach continuous magnetic fields of 45 T in the National High Magnetic Field Laboratory, Tallahassee, Florida.

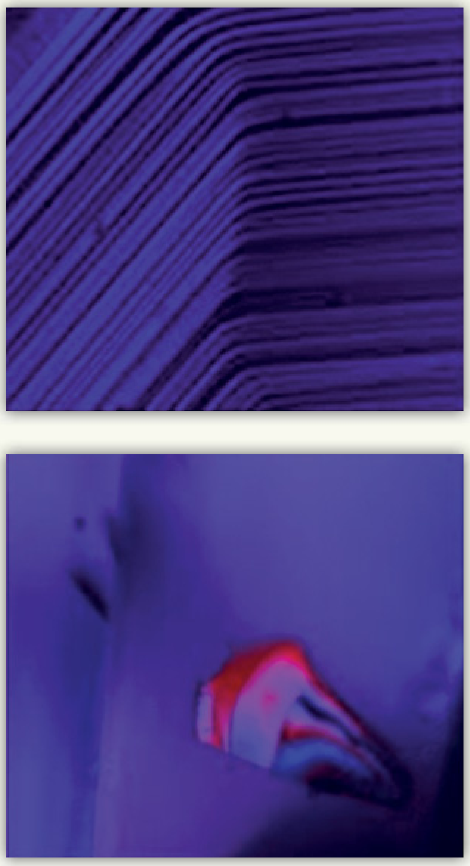

Fig. 4: Images of a single crystal of the quantum magnet $BaCu_2Si_2O_6$ grown in the laboratory. The image (top) shows the terraced growth spiral on the crystal surface. The image (bottom) shows a feature on the crystal surface at which the polarisations in different directions yield different colours.

Frustrated quantum magnets [3]

High magnetic field studies on itinerant electron systems have led to the measurement of various phenomena such as quantum oscillations in exotic materials including the cuprates. An important discovery that transformed theoretical condensed matter physics was the observation of remarkable plateaux in the off-diagonal resistivity in two-dimensional electron systems, which we now know to be a manifestation of the integer and fractional quantum Hall effects.

Our work on relatively less studied localised electron systems (Fig. 4) has revealed exotic new phenomena which are particularly interesting to compare and contrast with itinerant electron systems. Recently, our measurements of the quantum magnet $SrCu_2(BO_3)_2$ have found a rich hierarchy of plateaux in the magnetisation, rather than the Hall resistivity, as a function of magnetic field. In this case, the crossover between plateaux corresponds to transitions between different insulating magnetic ground states characteristic of this geometrically frustrated quantum magnet. Intriguingly, the fine sequence of magnetisation plateaux explored by our recent experiments evokes comparison with the integer quantum Hall effect in itinerant electron systems. Our experiments thus yield a potential route to a fascinating new class of states via geometrical frustration in strongly interacting spin systems.

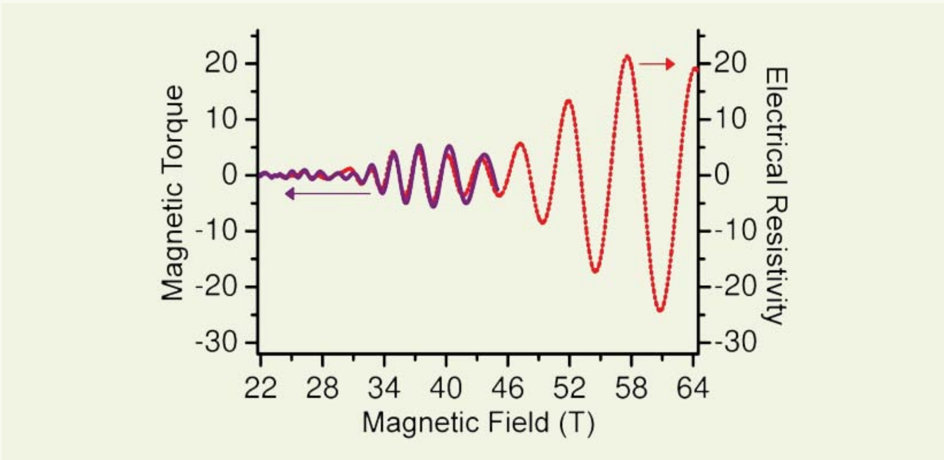

Fig. 3 Quantum oscillations measured in $YBa_2Cu_3O_y$, y=6.56, between magnetic flux densities 22 and 64T via magnetic torque and electrical resistivity. Label left: torque divided by magnetic field in arbitrary units. Label right: magnetic field integral of contactless resistivity divided by magnetic field squared, in arbitrary units. [1]

Iron-pnictide superconductivity under pressure [4]

The search for high temperature superconductivity has in recent years expanded from the copper oxide systems to a new class based on iron pnictides and chalcogenides. Using our recently developed material preparation laboratory (Fig. 5), we have synthesized a wide range of single crystals including $SrFe_2As_2$ and $BaFe_2As_2$. These appear at first to be conventional antiferromagnetic metals with Neel temperatures of the order of 100 K. We have discovered, however, that under applied pressures of over 30,000 atmospheres (Fig. 6) they become astonishingly good superconductors, with transition temperatures (T_c) close to that of the first discovered copper oxide superconductor. These studies in iron pnictides have established a new record in the maximum value of T_c achieved by the application of pressure to a material that is not superconducting at ambient pressure. By tuning carefully selected materials both via chemical doping and external pressure, we believe that many more families of high temperature superconductors will be found.

Outlook

The quantum phenomena described here are but a few examples of remarkable phenomena that have been discovered by combining materials' synthesis with techniques for tuning the starting materials under extreme experimental conditions. By further extending these techniques and exploiting their synergies, combined with insights gained from theory, we aim to enhance the role of design rather than serendipity in discovering new and enlightening forms of quantum order.

Suchitra Sebastian

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Fig. 5: High temperature furnace used in the laboratory for the preparation of single crystals by the flux growth technique.

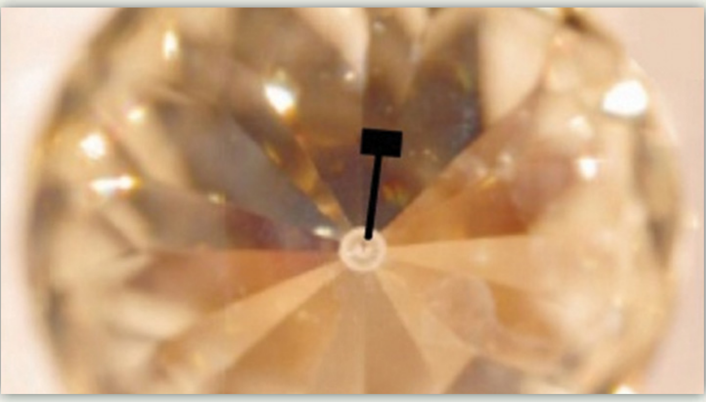


Fig. 6: A diamond anvil for high pressure research with inset microcoil of size ≈ 0.3mm.

Einstein's ideal

Recent experiments on ultra-cold atoms at temperatures below 1 microkelvin have confirmed precisely Einstein's prediction in 1925 that a new purely quantum state of matter exists for bosons as the temperature tends to zero.

The Bose-Einstein Condensation (BEC), predicted by Einstein in 1925, is conceptually one of the simplest phase transitions in nature, in many ways much simpler than the melting of ice or the boiling of water that we are familiar with in everyday life. In fact, it is the only transition between different states of matter that at least in principle does not require any interactions between the particles. According to Einstein's theory, it can occur even in an 'ideal', non-interacting gas, purely as a consequence of the laws of quantum statistical mechanics.

Einstein extended Satyendra Bose's pioneering work on the quantum statistical description of a gas of photons, or particles of light, to atoms and molecules, and came to a surprising conclusion. If one considers a gas of a certain type of identical atoms, now called bosons, at some fixed temperature, a relatively straightforward calculation shows that such a Bose-Einstein gas can contain only so many particles. Try to add any more and all the extra particles must accumulate in the lowest energy state, forming a macroscopic quantum object now known as a *Bose-Einstein Condensate*. In Einstein's own words, 'a saturation is effected; one part condenses, the rest remains a saturated ideal gas'.

This basic physical picture can be found in most textbooks and undergraduate physics courses. In practice, however, things are more complicated because particles do interact with each other, often very strongly. Moreover, interparticle interactions are not only hard to avoid, but are necessary for a gas to come to thermal equilibrium, a key assumption of Einstein's theory. One can therefore ask whether Einstein's picture of ideal-gas condensation can ever really be realised. It took 70 years to demonstrate something close to Einstein's ideal scenario, and recent work in the Cavendish's Atomic, Molecular and Optical Physics group (AMOP) shows that only now, another 16 years later, can we really declare victory.

In 1995 experimentalists achieved BEC in atomic gases so dilute, a million times thinner than air, and so weakly interacting that they were widely considered to have demonstrated a faithful illustration of Einstein's textbook picture. This feat required cooling a gas to dauntingly low temperatures, less than a millionth of a degree above absolute zero, and led to two Nobel prizes in Physics, in 1997 to Steven Chu, Claude Cohen-Tannoudji and William Phillips, and in 2001 to Eric Cornell, Wolfgang Ketterle and Carl Wieman. It also created a whole new field of physics. Today, more than 100 laboratories around the world use atomic BECs to study related quantum phenomena, such as superfluidity, and explore possibilities for applications in atom interferometry, precision sensors, navigation, and quantum computation.

While most efforts are focused on exploring ever more intricate new effects with ultracold atomic gases, even the 'basic' BEC transition still holds surprises. In recent experiments in AMOP (Fig. 1), we have shown that, under typical experimental conditions, atomic BECs actually deviate strongly from Einstein's picture of a condensation driven by a purely statistical saturation of the excited energy states in a gas. We have also shown, however, that the saturation picture is recovered in the limit of truly vanishing interactions, thus finally completing the experimental proof of Einstein's 86-year-old theory (N. Tammuz et al., *Phys. Rev. Lett.*, **106**, id. 230401, June 2011).

The key to these experiments is the ability to fine-tune the strength of interactions in an atomic gas, which for some atomic species can be achieved by applying an external magnetic field of variable strength (Fig. 2). In the complete absence of interactions there is no thermal equilibrium and so Einstein's *gedanken* experiment can never be realised directly. By studying the deviation from the saturation picture as a function of the interaction strength, however, it is still possible to show that Einstein's theory is correct in the limit of vanishing interactions (Fig. 3).

The ability to study the fundamental properties of the BEC phase transition as a function of the strength of interactions in a gas opens further exciting possibilities. For example, the effect of interactions on the critical temperature for condensation has been debated for more than 50 years, since the pioneering work by T. D. Lee and C. N. Yang. We can now test these theories with unprecedented precision, revealing for the first time the crucial role of quantum-mechanical correlations between interacting particles. Even more exciting are the possibilities to study the effects of interactions on the dynamics of condensate formation and its superfluid properties.

Zoran Hadzibabic

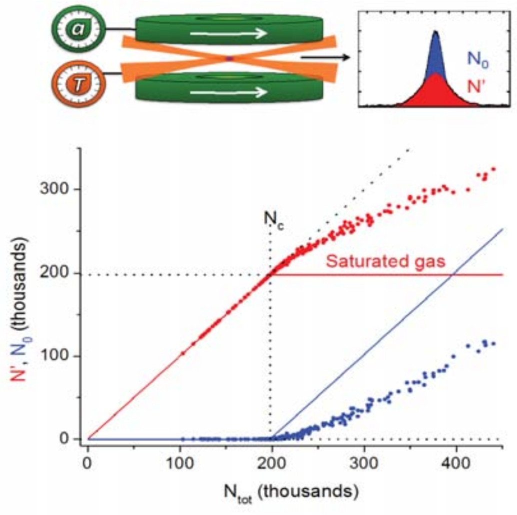


Fig. 2: Deviation of the experimental results from Einstein's textbook prediction. Even a weakly interacting gas, million times thinner than air, deviates strongly from Einstein's ideal-gas saturation picture, represented by the solid red and blue lines on the graph. A combination of lasers and magnetic fields is used to trap an atomic gas, cool it to a temperature T below a micro-kelvin, and vary the strength of interactions, characterised by the scattering length a. At a fixed T and a, we study the number of atoms in the condensate (N_0, blue) and the thermal gas (N', red) as a function of the total atom number N_{tot}.

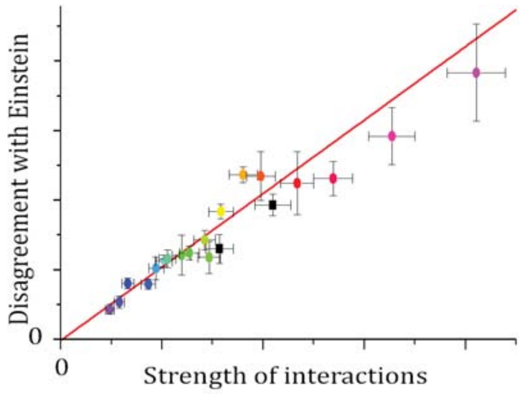


Fig. 3: Bose-Einstein gas saturation in the ideal gas limit. Tuning the strength of interactions and extrapolating to the non-interacting limit confirms Einstein's saturation hypothesis, even though direct equilibrium measurements in this limit can never be achieved. Each data point represents a data series, such as shown in Fig. 2, taken with a different set of experimental parameters.

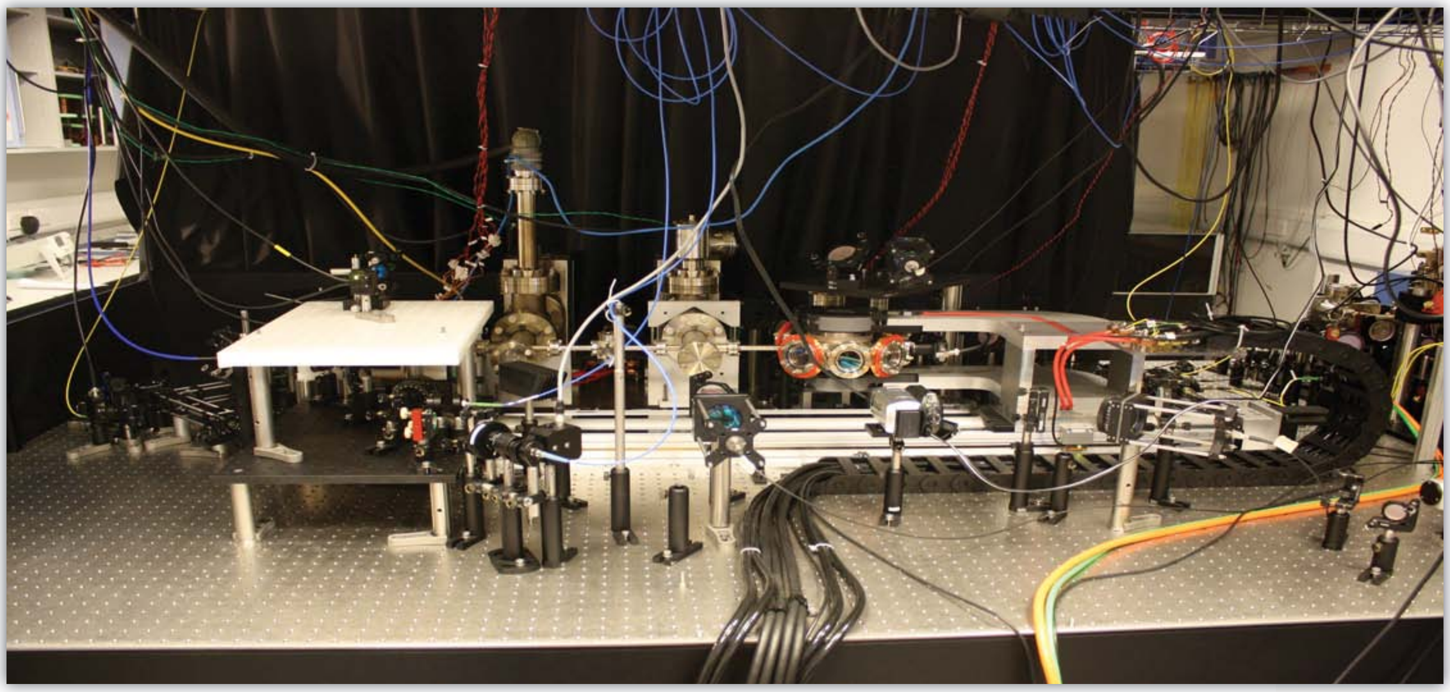


Fig. 1: The 'desk-top' apparatus developed to carry out experiments at the sub-microkelvin temperatures needed to realise the experimental conditions under which the phenomenon of the Bose-Einstein condensation can be observed and measured.

The Acoustical Experiments of Lord Rayleigh

John William Strutt, the third Baron Rayleigh (Figure 1), was the second Cavendish Professor, succeeding to the chair following the untimely death of James Clerk Maxwell in 1879. He agreed to hold the chair for five years, during which period his efforts were dedicated to establishing the laboratory as a world-class research and teaching laboratory. Notably, he opened all classes and demonstrations to the women of Girton and Newnham colleges. His principal research efforts during his tenure were the definition and establishment of electrical standards. After 1884, Rayleigh continued his experiments at his private laboratory at Terling Place, serving as President of the Royal Society from 1905 to 1908. In 1908, he returned to Cambridge as Chancellor of the University, a position which he held until his death in 1919.

Rayleigh's name is associated with a myriad of natural phenomena – the Rayleigh criterion in optics, Rayleigh fading, Rayleigh number, Rayleigh quotient, the Rayleigh–Jeans law, Rayleigh law, the Rayleigh distribution, the Rayleigh–Taylor instability, the Plateau–Rayleigh instability, Rayleigh–Bénard convection, the Rayleigh-Ritz method and so on. Among these achievements, his great two-volume work *The Theory of Sound* deserves a special place as one of the most influential treatises in classical physics.

But, he was not only a great theorist. He had a deep and lifelong interest in experiment and among these his acoustic experiments are of special importance. These are the subject of a splendid exhibition organised by the Whipple Museum and the Department of History and Philosophy of Science and sponsored by the Royal Society as part of its 'Local Heroes' project, celebrating the 350th anniversary of its founding. These displays include his kettledrum, used for testing his theory of the modes of vibration of two-dimensional sheets, simplified bells whose properties could be predicted by theory, the electrically maintained tuning fork and the Rayleigh disc for measuring the intensity of sound. The exhibition brings vividly to life Rayleigh's wide-ranging and deep understanding of physical phenomena. Many of Rayleigh's experiments, including the apparatus with which he isolated argon, are preserved at his laboratory at Terling Place, which can be visited by arrangement.

Although undoubtedly the complete master of classical physics, his theoretical work was to influence strongly the development of the quantum theory of matter. Two examples illustrate the significance of these researches. One was his discovery of the law of thermal radiation in the classical regime, what is now known as the Rayleigh-Jeans law. To derive this law, Rayleigh used his deep understanding of the modes of oscillation of a gas in an enclosure. He knew how to calculate these modes, assuming the law of equipartition of energy between independent modes, derived precisely the spectrum of black-body radiation in the long-wavelength limit. Although he could not derive the cut-off of the spectrum at short wavelengths, which requires the introduction of quantum concepts, the idea of treating the spectrum of the radiation as a statistical sum of the modes of vibration of light waves in an enclosure would eventually lead to Bose-Einstein and Fermi-Dirac quantum statistics.

Fig. 1: John William Strutt, 3rd Baron Rayleigh.

Fig. 2: Lord Rayleigh's Kettledrum.

Fig. 3: Lord Rayleigh's electrically maintained tuning fork.

The second example concerns Schrödinger's great papers of 1926. In Part 2 of his four-part paper entitled *Quantisation as an Eigenvalue Problem*, Schrödinger provided a detailed derivation of his wave equation. Then, he was able to use the complete exposition of eigenfunctions and eigenvalues contained in Courant and Hilbert's recently published *Methods of Mathematical Physics* (1924) to develop the theory of wave mechanics. Schrödinger remarked in the introduction to Part 3 of the series, in which he introduced perturbations into wave mechanics:

"The method is essentially the same as that used by Lord Rayleigh in investigating the vibrations of a string with *small inhomogeneities* in his *Theory of Sound*. This was a particularly simple case, as the differential equation of the unperturbed problem had *constant* coefficients, and only the perturbing terms were arbitrary functions along the string. A complete generalisation is possible not merely with regard to these points, but also for the specially important case of *several* independent variables, *i.e.* for *partial* differential equations, in which *multiple eigenvalues* appear in the unperturbed problem, and where the addition of a perturbing term causes the *splitting up* of such values and is of the greatest interest in well-known spectroscopic questions (Zeeman effect, Stark effect, Multiplicities)."

Thus, Rayleigh's techniques were precisely those that were needed for the development of wave mechanics. This might not have impressed Rayleigh, but it certainly had a profound influence on Schrödinger – the easy availability of the methods of orthonormal functions, perturbation theory and eigenvalues are all there in Rayleigh's *Theory of Sound*.

The Rayleigh exhibition will be open until the end of April 2012.

Malcolm Longair

Twisting Atomic Gases into Novel Quantum Phases

The central feature underpinning all research on novel electronic materials is the richness and complexity associated with the fact that the electrons behave as quantum many-particle systems. We all know that classical many-particle systems exhibit diverse forms of collective behaviour, notably the strikingly different properties of the common phases of matter, the solids, liquids and gases. Once the quantum nature of electron motion is thrown into the mix, there emerge even more exotic forms of collective behaviour for which our classical intuition quickly fails us. Examples include magnetism and superconductivity, which, while familiar concepts, require quantum theory to explain their origin. Less familiar are the quantum Hall effects which arise for electrons in semiconductors in strong magnetic fields, and the recently discovered 'topological insulators' and 'topological superconductors' whose properties and potential applications are still being explored. The richness and complexity of quantum many-body systems leave numerous unanswered questions, both for known materials, for example, what is the mechanism of high temperature superconductivity, but also, more generally, what other forms of collective quantum behaviour can exist?

Experiments on ultra-cold atomic gases offer the possibility of answering these questions and of leading to many new discoveries. These dilute gases of atoms, held in magnetic or optical traps, are cooled to such low temperatures, as low as a few nanokelvin, that the motion of the atoms must be described by quantum theory: the atomic de Broglie wavelength becomes larger than the interatomic spacing. The atomic gas then behaves as a quantum many-body system, with collective properties that depend on the nature of the atoms and on the atom-atom interactions. In some situations, the gases can mimic the behaviour of electrons in solid-state materials. Such studies hold out the prospect of exploring the physics underlying complex electronic materials. Moreover, ultra-cold atomic gases have the potential to uncover completely new quantum phases of matter: these could guide searches for similar phases in electronic materials, or have applications in their own right (see the articles by Michael Kohl in CavMag 4 and by Zoran Hadzibabic in this edition for descriptions of some of the current experimental work on ultra-cold atomic gases in the AMOP group).

Recent work in the Theory of Condensed Matter group has shown how to extend even further the capabilities of experiments on ultra-cold atomic gases. We have proposed novel forms of light field that cause the atoms to experience a *Lorentz force*. Our results open up the possibilities of using atomic gases to simulate the effects that magnetic fields have on electrons. Furthermore, the effective magnetic fields can be so strong that the atoms are expected to form novel quantum phases of matter.

How can one use light to exert a Lorentz force on a neutral atom? The crucial ingredient is the quantum nature of atom-light coupling. The combined atom-light system must be viewed as being in a quantum superposition of two states: a state A in which the atom is in its ground state and no photon has been absorbed from the light; and a state B in which the atom is in a long-lived, excited state and one photon has been absorbed. The amplitudes of state A or B in this quantum superposition can be made to vary in space by controlling the pattern of the laser fields. Then, as the atom

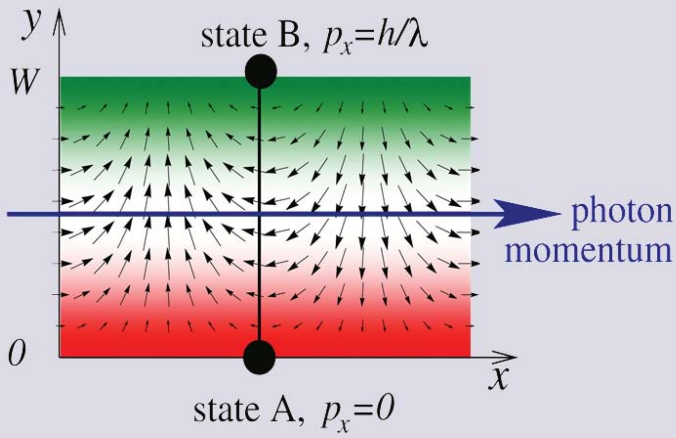


Fig. 1: A simple geometry of light fields in which a neutral atom experiences a Lorentz force. A laser propagates in the *x*-direction, with phase represented by the angle of the black arrows. As the atom moves from *y=0* to *y=W* it evolves from state A (red) to state B (green) in which one photon (of momentum $p_x = h/\lambda$) is absorbed from the laser. The momentum exchange with the light causes the atom to experience a transverse force analogous to the Lorentz force.

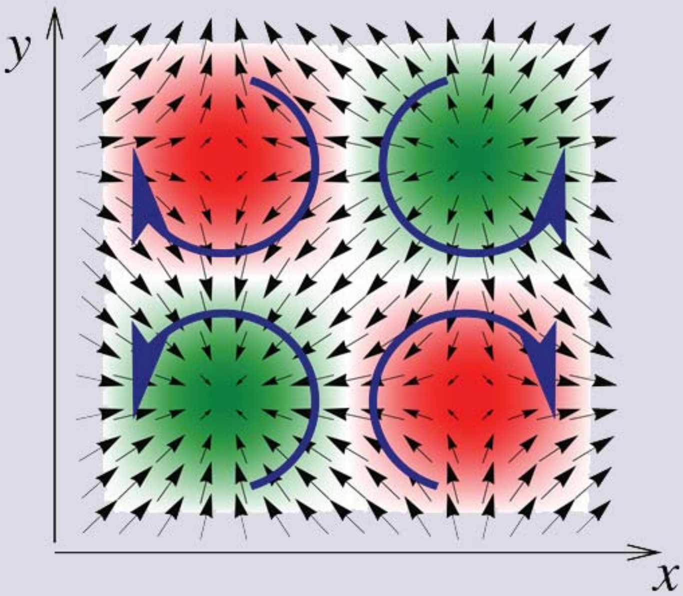


Fig. 2: A standing wave pattern of the laser leads to a lattice of vortices and anti-vortices of the phase of the light field (black arrows), corresponding to circulating photon angular momentum (blue arrows). An atom moving between regions in which its state is A (red) or B (green) exchanges momentum with the light in such a way that it experiences a Lorentz force equivalent to a magnetic field of fixed sign. [From N.R. Cooper, *Phys. Rev. Lett.* **106**, 175301 (2011).]

moves through space, it continuously changes between state A (no photon) and state B (one photon absorbed). Since photons carry momentum, the inter-conversion between A and B involves momentum exchange with the light field. Surprisingly one can form laser patterns such that this momentum exchange exactly replicates a Lorentz force. A simple set-up that illustrates the effect is shown in Fig 1, based upon an experimental scheme that has been used by Ian Spielman at the US National Institute of Standards and Technology (NIST). A laser is directed along the *x*-direction, such that the phase of the light field – indicated by the angle of the black vectors – increases by 2π as x increases by a wavelength, λ. A separate optical bias is applied such that on the line $y=0$ the atom is in state A (red), while on $y = W$ it is in state B (green). As the atom moves from $y = 0$ to $y = W$, its internal state gradually changes from state A (with no photon) to state B (with absorption of one photon). Since the photon has momentum h/λ in the *x*-direction, as the atom traces out this path, it picks up a momentum $p_x = h/\lambda$. This momentum builds up smoothly - for an atom moving at constant velocity v_y the momentum is $p_x(t) = (h/\lambda)(v_y t)/W$, which is equivalent to a force $F_x = dp_x/dt = (h/\lambda W)\, v_y$ This is a transverse force, just like the Lorentz force! A similar transverse force arises for atoms moving in the *x*-direction, in addition requiring considerations of the Doppler shift of the laser.

The scheme of Fig 1 leads to a relatively small effective magnetic field, scaling inversely with the overall width of the atomic cloud W which is many optical wavelengths – note that Fig 1 is not to scale. We have shown how to convert this into a very strong effective magnetic field. The key idea is to make a swirling pattern of vortices and anti-vortices in the optical field around which photons have circulating angular momentum of opposite senses (Fig. 2). Setting up a staggered optical bias that causes the atom to be in state A at the centre of a vortex (red) and state B at the centre of an anti-vortex (green) leads to a remarkable situation in which an atom that moves from the centre of any vortex to any anti-vortex, or vice-versa, experiences a Lorentz force corresponding to a magnetic field of the same sign.

From the point of view of the atomic gas, the effective magnetic field strength is huge. The Lorentz force will twist the trajectories of the atoms into tight circles, completely altering the collective behaviour of the gas. Experiments are underway to explore the consequences. The relevant physics involves the interplay of the quantum Hall effect with superfluidity (or superconductivity) in a manner that has never been previously achieved. For conventional superconductors this would require magnetic fields about a million times larger than in the strongest available magnets! Theoretical predictions include some very exotic 'non-abelian' quantum phases, which have been proposed as potential architectures for robust quantum computers but have so far never been found in nature. Leaving aside any such application, to detect these phases would greatly advance our understanding of quantum phases of matter, and for electronic systems as well. Most exciting, of course, is the possibility to discover something completely unexpected!

Nigel Cooper

© Michael Tompsett

Michael Tompsett awarded US National Medal of Technology and Innovation

We are delighted to report that Dr. Michael Tompsett has been awarded the US National Medal of Technology and Innovation, the highest honour bestowed by the United States government on engineers and inventors. The award is: 'For pioneering work in materials and electronic technologies including the design and development of the first charge-coupled device (CCD) imagers.' This is a lifetime award for six achievements in different areas of technological innovation that are still in use today. The Medal was presented in a ceremony at the White House in Washington, DC by US President Obama on October 21, 2011.

Mike was a Cavendish undergraduate at Jesus College from 1959-62 where he was supervised by John Adkins. He remained at Cambridge and Jesus College for his PhD but transferred to the Engineering Department. He received the Queen's Award in 1987 for his invention of a thermal imaging camera tube. In 2010, he was inducted into the NJ Inventors Hall of Fame in recognition of his pioneering lifetime achievements. More details of his inventions and career can be found at:

www.uspto.gov/about/nmti/recipients/tompsett.jsp

The First Science Museum Fellow of Modern Science

Many congratulations to Harry Cliff who has just been appointed the first Science Museum Fellow of Modern Science. Harry has just completed his PhD in the High Energy Physics group working on the LHCb experiment at CERN, which was described by Val Gibson in CavMag6. This project involves understanding the origin of the asymmetry between matter and antimatter in the Universe, and is going extremely well.

In this new initiative, masterminded by Val Gibson, Harry will be involved in the communication of fundamental science to the public through a dedicated exhibition about the Large Hadron Collider (LHC) and its science, as well as other new galleries on basic science that will be featured at the Science Museum in London. Harry's fellowship, to be held jointly between the Museum and the Cavendish, is the first of its kind to be sponsored by the Museum and the Isaac Newton Trust and is a marvellous opportunity to communicate the excitement and importance of basic science to the public. Ian Blatchford, Director of the Science Museum commented "This project is a unique opportunity to establish a special collaboration between Cambridge University and the Science Museum to communicate complex scientific research. We look forward to working with first class minds in this field and the benefits this brings for both institutions and those visiting the Science Museum".

Harry will also continue his research at the LHC, seeking new phenomena in high-energy proton-proton collisions. Harry is committed to the communication of science and has given numerous talks and lectures to schools and the general public. He is also engaged in the education of young people through his role as course leader at the Cambridge Teach First Access School, 2010 – 2011. He designed and led the two-day physics course for sixth form students from disadvantaged backgrounds with the aim of encouraging them to apply to top-flight universities.

Val Gibson, the Cambridge team leader for the LHCb experiment, commented: "The project has the potential for making major discoveries and, culturally, will enhance the experience of all who visit the Science Museum or read about its activities."

The CERN exhibition is expected to open in late 2013.

Watch this DSpace!

Alumni may be interested to know about DSpace@ Cambridge, the institutional repository of the University of Cambridge. The repository was established in 2003 to facilitate the deposit of digital content of a scholarly or heritage nature, allowing academics and their departments at the University to share and preserve this content in a managed environment. Increasingly it is expected that ideas and knowledge resulting from publically-funded research will be available through open access.

PhD students across the University are now encouraged to deposit their theses with DSpace once these have been approved by the examiners and gradually a collection of theses is being built up. The Cavendish collection can be viewed at **www.dspace.cam.ac.uk/handle/1810/198332**.

It is also possible for alumni to deposit their theses, and the Department and some alumni have done so. Peter Meek (Churchill) who studied for his PhD at the Cavendish from 1974 to 1977 under the supervision of Volker Heine recently deposited his thesis on DSpace. He writes:

"I find it very pleasing that after so many years [*my thesis*] is available on-line and, hopefully, much more readily usable by anyone who might care to refer to it. The process of dealing with DSpace and Cambridge University Library was simple, efficient and inexpensive, so I can recommend it to others."

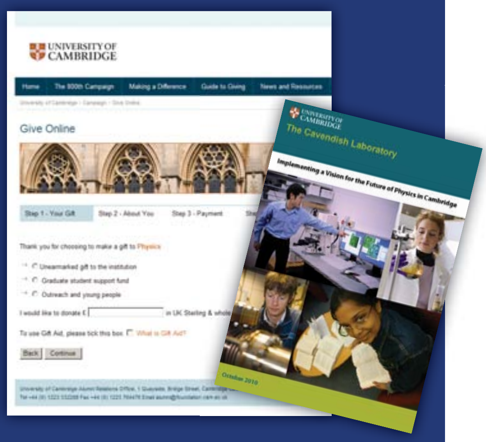
Peter's thesis is now available at **www.dspace.cam.ac.uk/handle/1810/238304**
It is the oldest thesis on DSpace – so far!

Any alumna or alumnus who is interested in depositing their thesis can find more information at **www.lib.cam.ac.uk/repository/theses**. Those wishing to know more about DSpace generally can consult **www.dspace.cam.ac.uk** where a wealth of information is available.

Robert Hay

Developing the Cavendish Development Plan

We have simplified the procedure for making gifts to the Development Programme. If you wish to make a donation, simply go to **www.phy.cam.ac.uk/development** and then click on **University of Cambridge Development Office's secure site**. This takes you to a page that explains the various ways in which donations can be made. Then click on **donate to the Cavendish Laboratory Development Programme** and that takes you to the Give Online page for Physics. There are three options, (i) an un-earmarked gift to physics, (ii) the Graduate student support fund and (iii) Outreach and young people. The value of the gift can be enhanced by using the Gift Aid procedure.



The various projects outlined in the **Cavendish Development Portfolio** span the complete range of activity within the Laboratory and are presented in order of increasing cost. But, it must be emphasised that gifts and benefactions at all levels are of enormous value to the Department. We will be most grateful for your support, at whatever level.

Evening Soirees at the Royal Society Summer Science Exhibition 2011

Members of the Cavendish were involved in two of the interactive hands-on exhibitions at the 2011 Royal Society Summer Science Exhibition.

The **High Energy Physics Group** collaborated with colleagues at the University of Birmingham in an exhibit entitled *Discovering particles - Fundamental building blocks of the Universe*. The hands-on experiments at the display included: the detection of cosmic-ray particles using spark and cloud chambers, the exploration of 3D computer images of high energy particle interactions live from the LHC and the transformation of Feynman diagrams into pictures of animals and plants.

The exhibit, *Colour in nature - How nature dresses to impress*, was presented jointly by the Cavendish Laboratory's **Nanophotonics (NP)** and **Biological and Soft Systems (BSS) Groups**, the University's Plant Sciences Department and the University of Exeter. The hands-on demonstrations included how to talk to live insects with invisible signals, playing the pollination and diffraction games and creating colours from your own interactive nanostructure replica.

Members of the High Energy Physics Group and the University of Birmingham at the Royal Society Summer Exhibition. From left to right, Harry Cliff (see also page 10), Steve Wotton, Cristina Lazzeroni (University of Birmingham), Mark Slater (University of Birmingham) and Sarah Williams. Cristina and Mark are former members of the HEP Group.

Members of the NP and BSS groups and the Department of Plant Sciences. From left to right Matthew Millyard, Pedro Cunha, Peter Cristroforini, Katrina Alcorn (Department of Plant Sciences), Ulli Steiner and Agnieszka Iwasiewicz-Wabring.

More Outreach Records

Physics at Work - record attendance

Bookings for the 27th annual *Physics at Work* exhibition were an all-time record – 2346 students attended the September event. The exhibition ran for three days from 20th until 22nd September, with two sessions each day (morning sessions begin at 9am and afternoon sessions at 1pm). The visitors were invited to vote for their favourite of the 25 exhibitions on offer. The honours were shared by the Atomic Weapons Establishment (AWE) and the Cavendish's Biological and Soft Systems (BSS) Research Sector. The winning exhibits involved strawberries and custard!

AWE demonstrated the power and properties of waves by blowing a house down with a custard powder explosion and making a row of flames dance to The Prodigy. The BSS team helped the teenagers extract DNA from strawberries, a reminder that the DNA code was unravelled at the Cavendish by two Cambridge physicists, James Watson and Francis Crick.

Details of how to apply for the 28th Physics at Work event, to be held from Tuesday 18th to Thursday 20th September 2012, can be found at: **www-outreach.phy.cam.ac.uk/physics_at_work/2012/index.php.**

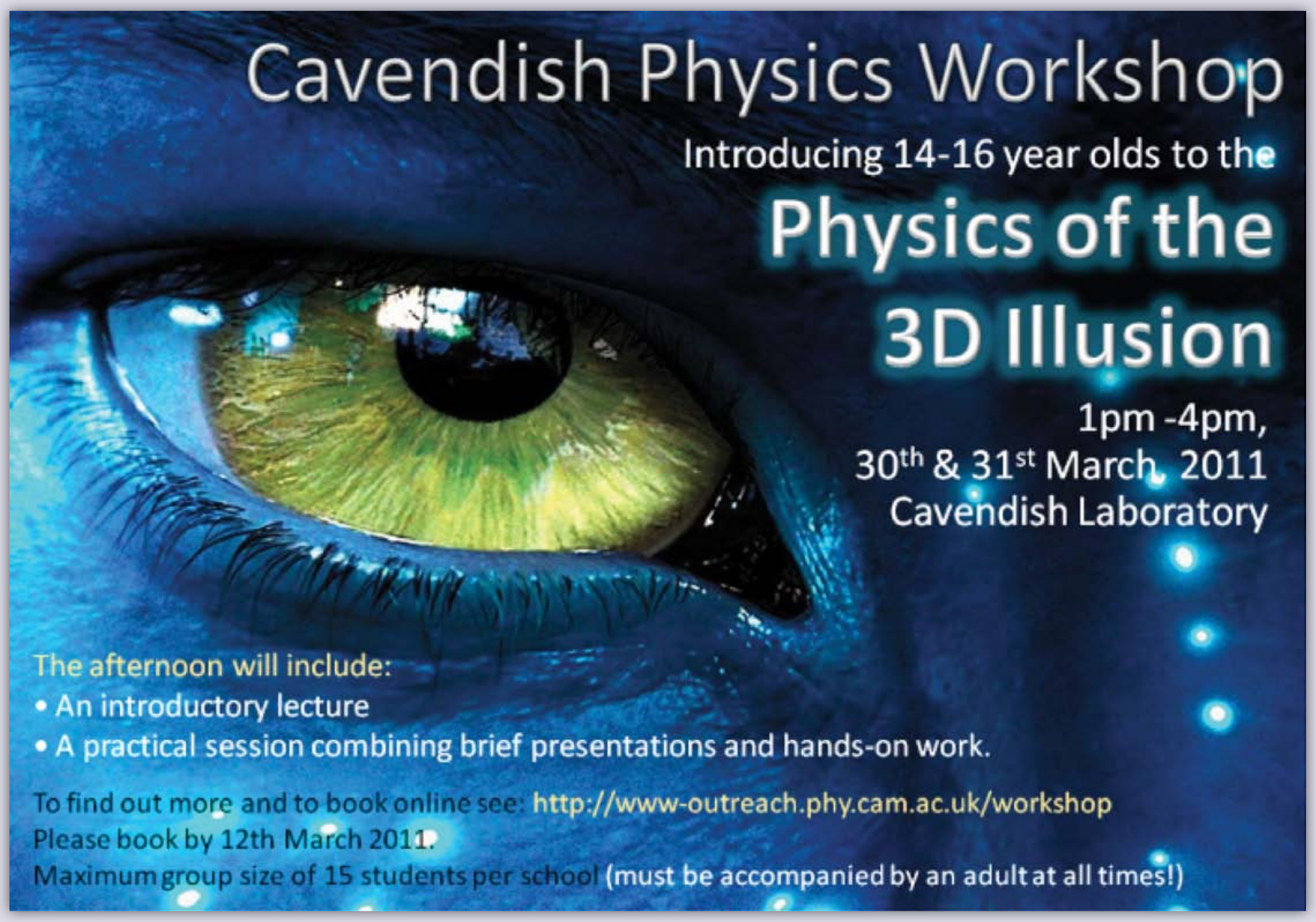
Booking opens on 7th May 2012.

School Workshops on the Physics of the 3D Illusion

On the 8th and 9th December 2011, 120 students, aged 11 to 13, visited the Cavendish for an afternoon of talks and practical workshops featuring the physics behind 3D movies and applying physics in the real world. The practical element of the workshop was developed by Dr Eileen Nugent of the Biological and Soft Systems Group at the Cavendish and sponsored by the Institute of Physics. The interdisciplinary nature of this workshop and its wide applicability has led to Dr Nugent and me integrating it with the undergraduate Part III education programme, and a student will be developing this workshop for the future. School workshops are held around March/April and December every year, the topics vary and interested teachers should go to our website to book online.

Cavendish Physics Teachers Residential Course

After the great success of our 2011 teacher residential pilot we are pleased to announce that we are opening applications for the 2012 event. From the 30th June to 2nd July, 20 places for A-level physics teachers from across the United Kingdom will be available for the 2012 residential workshop kindly hosted by



Robinson College and sponsored by the Ogden Trust. The aims and reasons behind this course are:

- Many talented students are unable to attend the student Senior Physics Challenge (SPC) as we just do not have enough spaces to host them. This opportunity will enable teachers to take the SPC back to school and into the classroom by providing the attending teachers with all the resources and background materials.
- An opportunity will be provided for first-hand experience of the Cambridge collegiate system and the base of physics research in Cambridge. The programme will include a session on Cambridge admissions from directors of studies in physics and admissions interviewers.
- We are keen to discuss ideas and concepts to further understand students' conceptual difficulties and bridge the gap between A-level and university physics.
- We aim to provide access to an inspirational environment in which to discuss physics and physics education with like-minded teachers, time out from school to refresh and think in alternative ways and experiment.
- The course provides an opportunity to observe the Senior Physics Challenge students in action.

For further information, teachers interested in booking a place should visit **www-outreach.phy.cam.ac.uk/Teacher-Res/index.php**

@PhysicsOutreach

Outreach at the Cavendish Laboratory can now be followed on twitter. Posts include physics puzzles to stretch students and updates of our events.

IOP Physics Update Course at the Cavendish

From the 16th - 18th December 2011, 50 teachers from across the country visited the Cavendish Laboratory and Churchill College as part of the Institute of Physics Update programme. During this time they participated in workshops, lectures and discussion sessions concerning all aspects of physics delivered by a variety of Cavendish experts including Malcolm Longair, Mark Warner and Andy Parker.

General

Information about all our outreach programmes can be found on our website **www-outreach.phy.cam.ac.uk**

More general residential and outreach initiatives are coordinated by the Cambridge Admissions Office in conjunction with the University departments, and further information can be found on their website at **www.cam.ac.uk/admissions/undergraduate/events**

Lisa Jardine-Wright

Physics at Work:
Extracting DNA from Strawberries

Physics at Work:
Students at the Rolls Royce stand building a model engine

Physics at Work:
How the LHC at CERN works

Winton Programme Funds New Appointments

The first cohort of six Winton Scholars joined the Cavendish in October 2011 to start their PhD programmes; they are shown above with their supervisors. Two are based in Theory of Condensed Matter working under the supervision of Mark Warner and Alessio Zaccone, and the others are spread between NanoPhotonics (supervisor - Jeremy Baumberg), Optoelectronics (supervisor - Richard Friend), and Microelectronics (supervisor - Henning Sirringhaus). The final Scholar is a joint appointment between Physics and Chemistry and will be developing new biologically-inspired materials for hydrogen production in the group of Erwin Reisner. These materials will be investigated in the optoelectronics group at the Cavendish.

Two Winton Advanced Fellows have been appointed to groups in the Cavendish to tackle very different but equally challenging problems that could have significant impacts on how we generate and store energy in the future.

Dr Alex Chin has been following the compelling experimental and theoretical evidence that has emerged over the last few years which suggest that non-classical properties of quantum mechanics may play an important role in the remarkably high efficiency and sensitivity of important biological processes, such as avian navigation, olfaction and photosynthetic light harvesting. His fellowship programme will investigate the general quantum design principles that optimise the performance of light-harvesting in natural photosynthesis, and then explore how these biologically engineered strategies might be used to improve man-made technologies, such as photovoltaic devices.

Dr Siân Dutton's work involves the chemical manipulation of materials to optimise their physical properties. She will work on new electrode materials for use in lithium-ion batteries for improved performance. These materials are often closely related to the strongly correlated electron systems investigated in the Quantum Matter group, and this connection will be developed. Siân's work will focus primarily on materials synthesis and characterisation. She aims to explore a number of new oxide based materials and, by chemical manipulation of their properties, optimise their performance. This work will bring new opportunities within the Cavendish and the University for developing these new materials and enable interactions with existing groups to expand the scope of her research programme. In particular the role of theoretical calculations to optimise the materials and to suggest new materials to study will allow for a more directed approach to materials discovery.

Both Scholarship and Fellowship appointments will be made annually to continue to expand research at the Cavendish and related departments in exciting new and novel areas in the broad field of sustainability. For further information contact the Programme Manager, Nalin Patel (**nlp28@cam.ac.uk**) or visit the Winton Programme website **www.winton.phy.cam.ac.uk.**

Left to right, above:

Back row – supervisors: Erwin Reisner, Mark Warner, Jeremy Baumberg, Richard Friend, Alessio Zaccone and Henning Sirringhaus.
Front row – students: (aligned with their supervisors) Nicholas Paul, Milos Knezevic, Jan Mertens, Michael Price, Breanndan O Conchuir and Milan Vrucinic.

Cavendish News

Richard Friend has been awarded the Harvey Prize 2011 of the Technion - Israel Institute of Technology. The citation reads: "In recognition of his outstanding contributions to science and technology, which are already making an impact on the semi-conductor industry and our lives."

Bryan Webber has been awarded the 2012 J.J. Sakurai Prize for Theoretical Particle Physics by the American Physical Society. The citations reads: "For key ideas leading to the detailed confirmation of the Standard Model of particle physics, enabling high energy experiments to extract precise information about Quantum Chromodynamics, electroweak interactions and possible new physics."

Jochen Guck has been awarded an Alexander von Humboldt Professorship to be held at the University of Dresden. The Humboldt Professorship is valued at up to five million euros, the most valuable international research award in Germany. He was also awarded the Institute of Physics 2011 Paterson Medal and Prize for his invention of the optical stretcher, as well as other novel physical probes to elucidate cellular mechanical and optical properties, their role in biological function and their potential in medical diagnostics.

Archie Howie has been awarded the 2011 Gjønnes Medal in Electron Crystallography, jointly with Michael Whelan of the University of Oxford, for the development of the dynamical theory of diffraction contrast of electron microscope images of defects in crystals, and other major pioneering contributions to the development and application of electron microscopy, diffraction and spectroscopy of materials.

We welcome **Emilio Artacho**, Professor of Theoretical Mineral Physics, who has transferred from the Department of Earth Sciences to the TCM Group in the Cavendish.

We congratulate **Ben Gripaios** on his appointment as a University Lecturer in Theoretical High Energy Physics. His research interests include developing methods for discovering and understanding physics beyond the Standard Model at the CERN Large Hadron Collider, working closely with experimentalists.

Warmest congratulations to **Mike Payne** on his election as an Honorary Fellow of the Institute of Physics. This award was in special recognition of his pioneering efforts in his IOP undergraduate recruitment initiative in the late '90s which led to approximately 4,000 student members joining the IOP before free e-membership was introduced. Their membership was paid for from the royalties of his company Accelrys.

Congratulations to **Montu Saxena,** in his role as Chairman of the Cambridge Central Asia Forum, on being awarded the Dostlik (Friendship) Order 'for huge contribution to the development of relations of friendship and partnership, cooperation with Uzbekistan and strengthening mutual understanding between the nations'.

Kevin Chalut has been awarded a Royal Society University Research Fellowship for 2011 on the subject, 'Developing photonics tools for understanding the physical world of stem cells'.

Brian Walker has been awarded a Herchel Smith Postdoctoral Fellowship to be held in the Optoelectronics Group.

Gunnar Moeller has won a Leverhulme Early Career Fellowship to be held in the TCM Group.

Richard Brierley of the TCM Group has been awarded the University of Cambridge's Hamilton Prize for his report on 'Non-equilibrium polariton condensate oscillations and their decay'.

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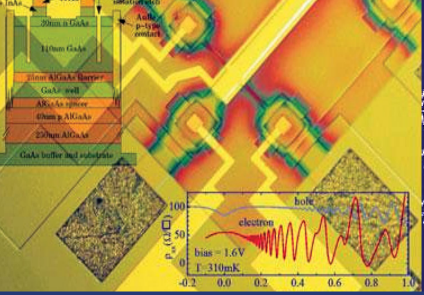 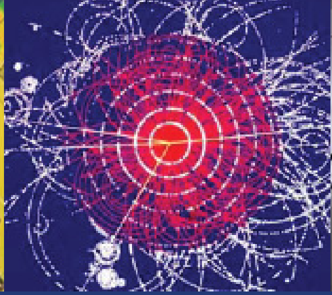  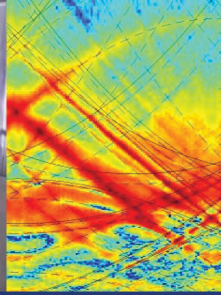 

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More transitions

30 September 2011 saw an unprecedented number of retirals among the support and research staff. We are most grateful for their enormous contributions to the work of the Department and wish them every success and happiness in all their future projects and activities. In alphabetical order, the retirees are: **Dennis Appleby, Rik Balsod, Sam Brown, Alan Chapman, Ray Flaxman, Ron Hodierne, Tracey Ingham, Alicia Kelleher, Gerie Lonzarich, Guy Pooley, Malcolm Templeton, Gerald Turner, Graham Winiecki and Fiona Winter.**

We record with great sadness that **Graham Winiecki** died soon after his retirement. We pass on our deepest condolences and sympathy to his family.

At the same time, many new faces appeared in the Department and they are all warmly welcomed. Their names and roles are as follows:

Anthony Barnett	Optoelectronics/Nanophotonics technician
Kimberley Cole	Group Administrator, Thin Film Magnetism and Surface, Microstructure and Fracture
John Flynn	Classes Technician (part-time)
Helen Jobson	Classes Technician (part-time)
Gary Large	Workshops
Jeremy Lewis	Graduate Students' Administrative Assistant
Dina Roshd	Scientific Computing Administrator (part-time)
David Taylor	Group Administrator, Quantum Matter, Inference and Structure and Dynamics
Helen Verrechia	Group Administrator, Theory of Condensed Matter

Above:
Ray Flaxman, Alan Chapman and their wives with Head of Department James Stirling at the Grand Retiral Party

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 James Stirling (HoD@phy.cam.ac.uk), who will be very pleased to talk to you confidentially. Further information about how donations may be made to the Cavendish's Development Programme can be found on page 10 and at: **www.phy.cam.ac.uk/development**

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