PHYSICS IN ACTION

Making light of a difficult phase

A new technique that allows attosecond control of light pulses could be used to steer electrons at a fundamentally new level

From **John Tisch** and **Jon Marangos** at the Department of Physics, Imperial College London, UK

Physicists are always striving to gain control over matter at the quantum level, and ultrafast lasers are just about the best way of achieving this. By precisely controlling the intensity, wavelength and duration of extremely short pulses of light, we can manipulate electronic processes at the atomic level. And if these pulses can be controlled at the scale of attoseconds, then the electromagnetic fields within them will be changing on the same timescale as the motion of the electron. This means that physicists can use the pulses to steer electrons with astonishing precision, and control processes such as the emission of light and chemical reactions.

Until now, however, there has been a fundamental obstacle to the control of such short pulses. At the level of a few femtoseconds, a laser pulse contains only a few cycles of the electromagnetic carrier wave. As the pulse evolves the carrier wave can become out of phase with the amplitude envelope (see figure 1), which can lead to a variety of different electric-field waveforms. This makes it difficult to put the pulse to any constructive use. The difference in phase between the carrier and envelope waves is called the carrier–envelope (CE) phase, and controlling it precisely is essential for a new generation of experiments that will probe and manipulate processes that occur on a sub-femtosecond timescale.

Now physicists in Vienna and Germany have managed to do just that, allowing the CE phase of a high-power ultrashort pulsed laser to be altered at will. With this set-up they were able to control electrons at the scale of 250 as (250×10^{-18} s), and they claim that their technique is limited only by the most fundamental barrier we know – quantum-mechanical uncertainty (A Baltuška *et al.* 2003 *Nature* **421** 611–615).

Ever-decreasing light

The shortest pulses are produced by using near-infrared lasers that have an optical period of about 2 fs. For pulses that are much longer than this, a change in the CE phase cannot be detected because the amplitude envelope changes very little between cycles. However, in the last few years huge strides have been made in producing ever-shorter pulses, and laser-based sources that produce pulses as short as 4 fs are now available (see "From femtochemistry to attophysics" by Ferenc Krausz *Physics World* September 2001 pp41–46). The role of the CE phase is now critical.

Phase control – physicists Matthias Uiberacker and Eleftherios Goulielmakis at the Technical University in Vienna are using ultrafast lasers to control processes at a fundamental level.

In 1999 Ferenc Krausz and Thomas Brabec, who was then at the Technical University in Vienna, recognized that the measurement and control of the CE phase constitutes one of the most challenging problems in ultrafast optics. This is because the envelope and the carrier wave travel at different speeds in optical materials, which causes them to continuously slip in and out of phase (see figure 1). The optical materials in lasers can cause the trains of pulses that are emitted to have effectively random CE phases – even if all the other pulse parameters are kept constant.

It has recently become possible to stabilize the CE phase of ultrashort pulses from titanium-doped sapphire laser oscillators. However, the pulses from such lasers have energies of just 1 nJ – too puny to drive the nonlinear processes in atoms that are predicted to be most sensitive to this phase. One such process is routinely harnessed to make tabletop sources of soft X-rays, where high harmonics are generated in atoms by a very intense laser pulse.

Andrius Baltuška, Krausz and co-workers at the Technical University in Vienna, and collaborators from the Max-Planck Institute for Quantum Optics in Garching, claim that they have now gained control of the CE phase. They were able to produce pulses with stable phases that are about one million times more intense than previously obtained, at a rate of 1000 pulses per second. Their system comprises a laser oscillator with a stabilized CE phase and a laser amplifier to massively boost the energy of the oscillator pulses. The amplifier introduced relatively slow changes in the phase, against which the light pulses had to be stabilized. Baltuška and colleagues cracked this technically challenging problem by pre-compensating the oscillator CE for these drifts with an additional feedback loop.

The researchers demonstrated that they could control the relative CE phase of their near-infrared 5 fs pulses with a resolution of about 100 as and residual fluctuations of less than 20 as. For the first time a powerful light source with just a few cycles is available that is capable of producing pulses with a highly reproducible and controllable electric-field waveform.

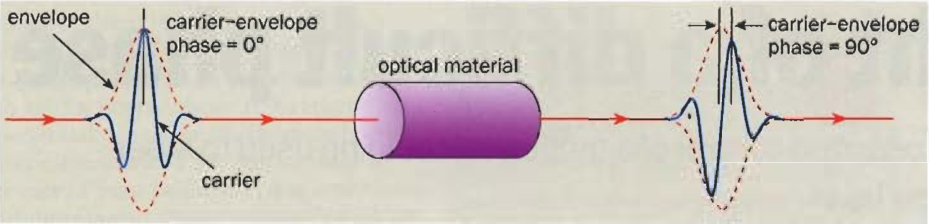
Short and soft

The researchers were quick to put this new light source into action. They focused their laser pulses on neon gas and measured the soft X-ray spectrum of the light produced in this interaction using a spectrometer. The effect of the oscillating electric field of the laser pulse on the atoms is to rock the potential well that normally confines the electron. Above a certain field-strength threshold the electron can be tipped out. This is called optical field ionization of the atom, and it requires an electric field strength of about 5×10^{10} V m^{-1}.

Once it is free of the nucleus, the electron is accelerated in the laser field only to be slammed back into the nucleus when the field direction is reversed about half a period (1 fs) later. In the resulting collision the electron can return to its ground state, giving up the kinetic energy it has gained in the form of a soft X-ray photon. When a large number of atoms in a gas are illuminated by the same laser pulse, the result is an intense attosecond burst of soft X-rays that is emitted in a laser-like beam.

Baltuška and co-workers focused their attention on the photons that were emitted with the highest energies – in the "cut-off" region of the spectrum between 120 and 130 eV. These photons come from the electrons that had the highest kinetic energy when they collided with the nucleus. Thomas Brabec and others had predicted that this cut-off region would be highly sensitive to the CE phase for these very short pulses. This is because the maximum collision energy is only reached if the electric field of the light pulse evolves in exactly the correct form – and this evolution is critically dependent on the CE phase.

The team has emphatically confirmed these predictions with its measurements. For a CE phase of 0° the researchers observed



1 The carrier wave (blue) and envelope (red) of a light pulse move at different speeds in an optical material. These can be out of phase by an amount known as the carrier–envelope phase.

a smooth spectrum in the cut-off region, which is the signature of a single collision of maximum energy that gives rise to a single burst of cut-off photons. When they changed the CE phase to 90°, they measured a strongly modulated cut-off spectrum. This is evidence for two temporally separate bursts of photons, which produced an interference pattern similar to the fringes seen in a Young's double-slit pattern. In fact, the experimental data were so clear that the researchers could use this collision process as a "detector" to determine the absolute CE phase. When they switched off the stabilization of the phase, the features in the spectrum became washed out because of the random fluctuations of the electric-field waveform from one laser pulse to the next.

The importance of this result is that physicists can now control precisely when the ionization and collision of an electron from an atom or molecule will occur using intense few-cycle light pulses. A full description of this process requires the electron to be defined in terms of its wavefunction, which is subject to quantum-mechanical uncertainty. However, with ultrafast light pulses that have their CE phases stabilized, we can now control the motion of the electron down to an unprecedented limit – that set by the uncertainty principle.

Researchers are planning to use the bursts of attosecond radiation emitted at precisely defined times to make measurements of extremely fast processes that have not been accessible until now. These include the electronic changes that determine how matter is bound together, and how physical and chemical changes occur. This is a fundamental level of control, and these developments are therefore very exciting.

Astrophysics and air travel

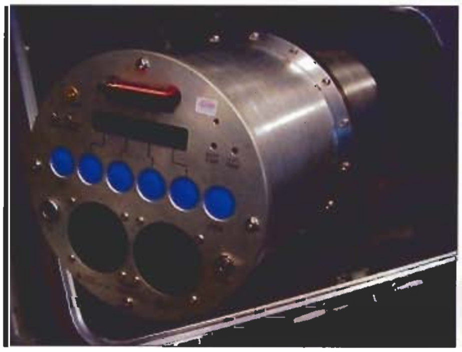
A proportional counter that mimics human tissue can measure cosmic-radiation exposure at high altitudes

From **Graeme Taylor** at the National Physical Laboratory, Teddington, UK

If you have a fear of flying, then probably the last thing on your mind when you are 10 km above the ground is what might be going on in the depths of the galaxy. But airline pilots and cabin crew might want to brush up on their astrophysics. High-energy particles coming from violent galactic events mean that radiation exposure for aircrew is higher than it is for most people classified as radiation workers. But the type of radiation that they are exposed to is very different.

The majority of the exposure comes from cosmic radiation that originates outside our solar system. Violent events such as stellar flares, supernovae and the explosion of galactic nuclei produce a concoction of subatomic particles, primarily protons and electrons. The energies of these particles can be greater than 10^{20} eV – billions of times higher than in the most powerful particle accelerators – although such energetic particles are very rare. Nuclear particles, which comprise about 98% of the radiation, typically have energies that are between 100 MeV and 10 GeV per nucleon.

On the surface of the Earth the atmosphere shields us from almost all of this radiation, but at the altitudes at which aircraft fly the levels of radiation are about 150 times higher – and the aircraft itself offers no protection. The impact of the galactic radiation on molecules in the upper atmosphere results in the generation of neutrons from nuclear interactions and electrons from electromagnetic cascades. It is these two particles that are the dominant sources of exposure for aircrews, in roughly equal measure (see "Cosmic rays: an in-flight hazard?" by Denis O'Sullivan *Physics World* May 2000 pp21–22).



High flyer – it may not be on everyone's packing list, but the tissue-equivalent proportional counter is an important device for measuring the exposure to cosmic radiation when flying.

Plastic tissue

In 1999 the neutron metrology group at the National Physical Laboratory in the UK was contacted by the Civil Aviation Authority to ask if we had any instrumentation that would be suitable for measuring the radiation exposure of aircrew. By coincidence, we were in the process of evaluating just such an instrument for a company called Far West Technology in California. The instrument in question was a tissue-equivalent proportional counter (TEPC) that was bundled with prototype electronics. The whole system fitted into a small suitcase and was battery powered, which meant that it could be left onboard an aircraft for several days at a time to measure the radiation doses on particular routes.

The TEPC is based on a spherical proportional counter. A thin outer casing of aluminium holds a spherical shell made from conducting plastic that is about 0.2 cm thick and encloses a gas cavity approximately 12.5 cm in diameter. The plastic is a special combination of polythene, nylon, graphite and calcium fluoride, which are mixed in such a way that the overall composition is similar to that of human soft tissue. It is the presence of the graphite that gives the plastic its conducting qualities, albeit very poor ones. The filling gas used is propane, which has a composition similar to that of tissue.

It is here that the operation of the TEPC starts to deviate from a more orthodox proportional counter. Traditional counters tend to be filled to pressures of one or more atmospheres, but the TEPC is only filled to about 0.01 atmospheres. This means that most of the events detected originate in the plastic wall rather than the gas, and also that the majority of the particles cross the entire counter rather than stopping.

The tissue equivalence of the TEPC means that when cosmic radiation interacts with it, the reactions are similar to those that would be produced in living tissue. This alone means that the TEPC gives a reasonable measurement of the absorbed radiation dose. In addition the ionization that is produced by charged particles that cross the counter is equivalent to the amount that would be produced in a volume of tissue smaller than a human cell. This is sufficiently small that the counter effectively samples the rate at which a particle deposits energy, which can be related to how damaging the particle is to tissue – normally called the particle's radiation quality.

By combining the measurement of the absorbed dose with the derived value for the radiation quality, a value for the dose equivalent in sieverts can be calculated. The upshot of this rather convoluted process is that the TEPC response is closely related to the amount of tissue damage caused by exposure to radiation, particularly for those particles and energies found in cosmic-radiation fields at high altitude.

In practice there are many complications to this rather simplified approach, such as the assumption that the TEPC is fully tissue equivalent, which is not valid at all energies. As a result, the TEPC is calibrated in terms of dose-equivalent response in the simulated-cosmic-ray facility at CERN. Nevertheless, the TEPC is generally considered to be the best instrument for performing cosmic-ray dosimetry in aircraft.

By the end of 1999 a collaboration had been established between the National Physical Laboratory, the Civil Aviation Authority, the Mullard Space Science Laboratory and Virgin Atlantic Airways to perform dose measurements on airline routes with TEPCs. These began in early 2000 and are still ongoing. By the end of last year the collaboration had used five TEPCs to measure doses on over 500 flights. These flights were mostly on Virgin Atlantic commercial routes from London to destinations in South Africa, the US, Europe and the Far East. Several groups are also using these data to validate computer models of dose rates, and recently the European Commission's DOSMAX group, which has been performing measurements with a variety of different devices, has offered to accept these additional TEPC measurement data.

The collaboration has also been investigating possible correlations between doses and unusual solar activity – generally known as space-weather effects (see "Space weather: physics and forecasts" by Janet Luhmann *Physics World* July 2000 pp31–36). So far the only space-weather effects observed have been the daily modulation caused by the Sun's activity. Measurements of radiation dose have been made during two significant solar flares but no elevated doses were recorded at flight altitudes. It is known, however, that some flares do lead to elevated doses at altitude, and it is the tell-tale signs in the build up to such flares that we are trying to identify.

With another two years to run on the project, it may be possible to reach 1000 flights in total. Furthermore, although the probability of observing a major solar event is small in the current phase of the solar cycle, it is still a possibility. But regardless of any interesting solar activity, a self-consistent database of doses and aircraft routes will enable us to validate predictive computer models more precisely.

Exploding excited electron bubbles

First observations of excited electron bubbles in superfluid helium reveal puzzling features

From **Peter McClintock** in the Department of Physics, Lancaster University, UK

The "particle in a box" is a standard second-year quantum-mechanics problem, much beloved by lecturers and mastered (or not) by successive generations of undergraduates. An electron bubble in liquid helium provides a strikingly simple example of this kind of system, and theory predicts that it should exhibit a series of excited states. But these states have never been demonstrated experimentally. Now Denis Konstantinov and Humphrey Maris of Brown University in the US have observed one of these excited states for the first time by exploding electrons bubbles with sound waves (D Konstantinov and H Maris 2003 *Phys. Rev. Lett.* **90** 025302).

When an electron is placed in liquid helium, it expels about 1000 helium atoms from around itself and creates a vacuum bubble that contains nothing but its wavefunction. The size of the bubble is determined by the interplay of various energy contributions. Larger bubbles reduce the zero-point energy of the electron – the minimum energy that it can have due to quantum-mechanical uncertainty – but at the same time they have a greater surface energy than smaller bubbles. If there is a finite ambient pressure then the volume energy of the bubble will also increase.

There is therefore an optimal bubble size that minimizes the total energy. When the electron is in its 1s ground state, the resultant bubble is spherical with a radius of 1.9 nm for zero applied pressure. With its negative electronic charge, the bubble is a semi-macroscopic object that is often somewhat misleadingly called a negative ion.


Exciting stuff – electron bubbles can be exploded to giant sizes that enable them to be detected with a He–Ne laser.

Blowing bubbles

Electron bubbles have proved to be exceedingly useful probes of superfluid helium-4, which is otherwise hard to study because it is inert. They can be formed easily by injecting electrons into the liquid helium using a sharp metal tip, and their subsequent arrival at any point in the apparatus can be registered as a current. Electron bubbles have been used for several important experiments on superfluid helium-4, such as a measurement of the Landau critical velocity at which superfluidity breaks down, and for studying the creation and decay of quantized vortices and superfluid turbulence.

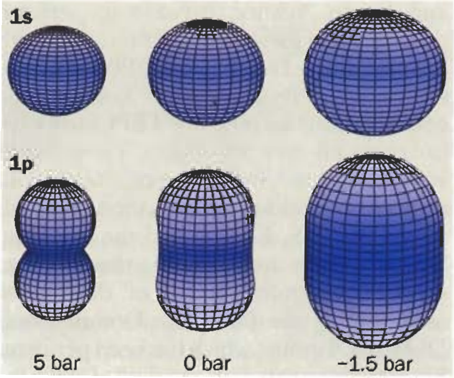
These experiments use ground-state electron bubbles, in which the trapped electron is in its 1s state. But electron bubbles also have excited states. Here the average radius and shape of the bubble will be different because the internal pressure and symmetry of the electron wavefunction will not be the same.

Calculations of the form of the bubble for different applied pressures – also made by the Brown group – yield interesting results for the 1s and 1p states (see figure 1). With positive applied pressure, the vacuum–helium interface that "dresses" the electron is pressed tightly around it, and the shape of the wavefunction impresses itself strongly on the bubble. This is clearly seen for the 1p state at a pressure of 5 bar. But as the pressure is reduced the bubble grows and loses its "waist".

Until now it has been far from clear how any of these phenomena might be demonstrated experimentally. Maris and Konsantinov applied a strong acoustic field to the bubbles and measured the negative pressures at which they became unstable. They operated an ultrasonic transducer at 1.4 MHz, which produces waves with a period that is longer than the few picoseconds that it takes for the bubble to equilibrate. The bubble therefore perceives the acoustic field as a quasi-static change in the ambient pressure.

Their calculations show that there is a critical reduced pressure at which the growing bubble becomes unstable and explodes because the surface tension is no longer capable of holding it together. The critical pressures are calculated as –1.89 bar for the 1s bubbles and –1.63 bar for the 1p bubbles.

The researchers first injected electrons into liquid helium from a tungsten tip and then used a CO_2 laser to excite some of them into the 1p state. Next they used the cyclic acoustic field to expand the bubbles to giant size (explode) and then shrink them again. If this change in pressure is sufficiently large, then the bubbles will be momentarily large enough to scatter enough light from a second He–Ne laser that they can be detected using a photomultiplier. In doing this, Konstantinov and Maris found that the 1p bubbles apparently begin to become unstable at a transducer voltage that is about 18% less than that for the 1s bubbles, which is in reasonable agreement with the calculated value of 14%.



1 Electron bubbles in the 1s ground state (top) and 1p state (bottom) at three different pressures. Previously Maris suggested that the electron may divide into two parts if the waist of the bubble pinched off.

Divided views

These results are very satisfying. However, Konstantinov and Maris suggest that there are even more important things to come. Their main results were obtained at 1.8 K, but below 1.4 K they observed quite different and unexpected behaviour. At 1 bar, for example, the CO_2 laser did not appear to produce any 1p bubbles at all. Rather, it created new entities that were actually harder to explode than the ground-state 1s bubbles. They also survived much longer – in excess of 10 ms compared with the 1p bubble lifetime of 40 μs.

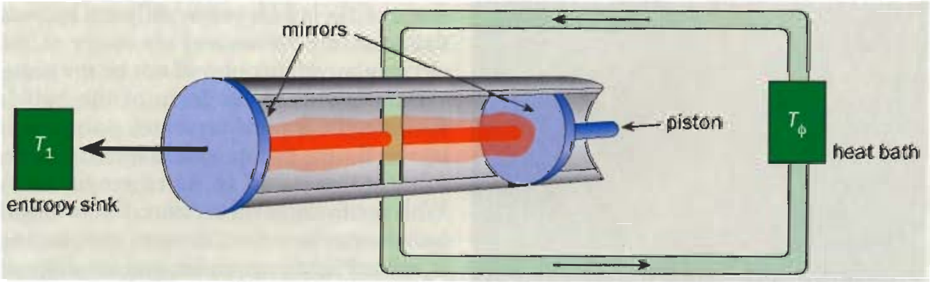
It is not known yet what these entities are, but it is intriguing to note that they appear under just the same conditions as Maris's prediction of counterintuitive effects in 2000.

At these lower temperatures the normal, viscous-fluid component of liquid helium is reduced compared with its superfluid component, which means that the motion of the bubble in the 1s to 1p transition is less damped. As its shape changes from being like one of those shown in the top of figure 1 to being like one in the bottom, the inertia of the moving liquid will result in an overshoot. In other words, the waist on the bubble may eventually pinch off completely.

Maris's earlier suggestion that this would inevitably divide the electron into two parts has unsurprisingly proved controversial, and his experiments are ongoing. Whether or not the recently discovered low-temperature entities are associated with the idea of electron splitting is not known. But they are at least very intriguing. The next stage in this research is eagerly awaited.

Photon steam engines

Work can be extracted from a single heat bath at the boundary between classical and quantum thermodynamics



A quantum Carnot engine. Hot atoms flow from a heat bath at temperature T_φ to an entropy sink at a lower temperature T_1. The atoms exchange energy with photons in an optical cavity, which drive a piston.

From **Peter W Milonni** at the Los Alamos National Laboratory, New Mexico, US

Modern society relies heavily on the conversion of heat into mechanical work. The first heat engines were responsible for the industrial revolution, but behind the scenes they were also fuelling the development of thermodynamics. In 1824 Sadi Carnot's interest in improving the performance of steam engines led him to think about the efficiency of a heat engine in a new and fundamental way. He concluded that the maximum efficiency of a heat engine that absorbs heat from a reservoir at a given temperature, T_2, and rejects heat to another reservoir at a lower temperature, T_1, is $\eta = 1 - T_1/T_2$. In other words it is impossible to extract work from a single heat bath – a rule that we now know to be a consequence of the second law of thermodynamics.

Then came quantum mechanics. Classical thermodynamics tends to work for large numbers of atoms or molecules, which means that some quantum systems can at first appear to violate its basic laws. Now Marlan Scully and co-workers at Texas A&M University and Herbert Walther at the Max-Planck Institute for Quantum Optics in Garching have proposed a "quantum Carnot engine" that displays features that are simply not possible with a classical engine. In particular, their quantum engine can extract work from a single heat bath (M O Scully *et al.* 2003 *Science* **299** 862–864).

Quantum steam

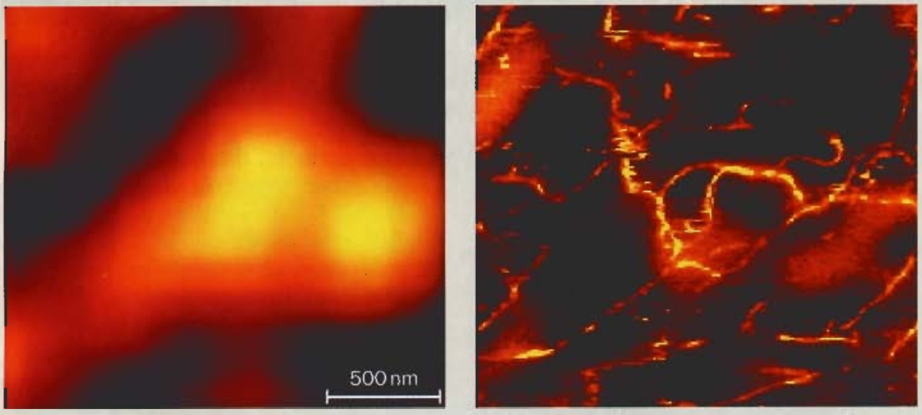
Carnot's conceptual heat engine operated in cycles such that there is no change in the internal energy of the working fluid – such as steam – during a cycle. More heat is converted to work as the number of operating cycles increases, without the engine itself being a source of any work. In particular he considered a reversible closed cycle consisting of two isothermal (constant temperature) processes and two adiabatic (no external exchange of heat) processes. He showed that no heat engine operating between two temperatures could be more efficient than a Carnot cycle. But he was wrong.

The "steam" in the new quantum Carnot engine considered by Scully and colleagues comes in the form of photons. The radiation pressure from the photons drives a piston in an optical cavity, which also doubles as one of the cavity mirrors. The other cavity mirror is used to exchange heat with a heat sink at temperature T_1. A second heat bath at a higher temperature T_2 is required as a source of heat for the radiation, in analogy with the classical Carnot engine.

Scully and co-workers take this source of heat to be a stream of hot atoms, which flows through the cavity and exchanges energy with the photons through emission and absorption processes. These atoms flow out of the cavity at a cooler temperature and are then reheated in a second cavity known as a "hohlraum". Once the atoms have been heated to T_2 they are re-injected into the first cavity for the next cycle of the quantum Carnot engine (see figure).

The quantum and classical Carnot engines therefore operate in the same way – a closed cycle of two isothermal and two adiabatic processes. However, in its simplest form the quantum Carnot engine cannot extract work from a single heat bath. If Q_{in} is the energy absorbed from the bath atoms during the isothermal expansion and Q_{out} is the energy given to the heat sink during the isothermal compression, then the efficiency of the engine is $\eta = (Q_{in} - Q_{out})/Q_{in}$. If the

Optical microscopy sets new record



Physicists have used a technique known as near-field Raman microscopy to produce the highest ever resolution in an optical image (A Hartschuh *et al.* 2003 *Phys. Rev. Lett.* **90** 095503). The image of carbon nanotubes on the left was obtained with a conventional far-field microscope, while the one on the right is the same sample imaged using the new technique. Raman spectroscopy involves passing laser light through a sample and measuring how it is scattered. It can provide much more detailed structural information about molecules than other imaging methods because it measures the vibrational modes of a material.

bath atoms are assumed to be two-state systems that absorb and emit radiation at the same frequency, then standard thermodynamic formulas for the photon gas reveal that the efficiency of the quantum Carnot engine is $\eta = 1 - T_1/T_2$ – just as it is for the classical Carnot engine.

Quantum coherence

The new twist in the quantum engine occurs when the bath atoms have three states instead of two, which can result in what is called quantum coherence. If there is a non-vanishing phase difference between the two lowest atomic states, then the atoms are said to have quantum coherence. This can be induced by a microwave field with a frequency that corresponds to the transition between the two lowest atomic states.

Quantum coherence changes the way the atoms interact with the cavity radiation by changing the relative strengths of emission and absorption. The idea is that the atoms leaving the hohlraum at temperature T_2 pass through a microwave cavity that causes them to become coherent with phase ϕ before they enter the optical cavity. They still cause the cavity radiation to come into thermal equilibrium, but the temperature that characterizes the radiation is now $T_\phi = T_2(1 - n\varepsilon\cos\phi)$, where n is the average number of photons for a thermal field at temperature T_2, and ε is a small number that characterizes the magnitude of the quantum coherence.

The efficiency of the quantum-coherent Carnot engine can then be expressed as $\eta_\phi = (T_\phi - T_1)/T_1$. If ε is small, this becomes $\eta_\phi \sim \eta - (T_1/T_2)n\varepsilon\cos\phi$, where η is the efficiency of a classical Carnot engine as before. Thus, depending on the value of ϕ, the efficiency of the quantum Carnot engine can exceed that of the classical engine – even when $T_1 = T_2$. It can therefore extract work from a single heat bath.

And the second law?

At first glance this might seem trivial, since the atoms leaving the hohlraum are simply made hotter by the microwave generator, causing the radiation field to become hotter than the temperature of the hohlraum. This is not the case. Microwave heating of the atoms has no direct effect on the temperature T_ϕ of the cavity radiation. It is the quantum coherence that is induced by the microwave that makes T_ϕ different from the hohlraum temperature. There is, of course, a cost for this coherence – the microwave energy required to produce the coherence must exceed the net energy that is extracted from the heat bath.

Furthermore, extracting work from a quantum Carnot engine does not violate the second law of thermodynamics because the quantum coherence also costs extra entropy, which ensures that the overall entropy of the system is always increasing.

Practicalities aside, a quantum Carnot engine may one day provide a "quantum afterburner" that will increase the efficiency of a conventional combustion engine. Such a hybrid device would exploit the temperature difference between the combustion and exhaust phases of the four-stroke Otto cycle (see "The energy-saving quantum afterburner" *Physics World* March 2002 p6).

The point is that atoms with quantum coherence constitute a substance that is fundamentally different from conventional working fluids such as steam or Freon, which allows us to extend our understanding of thermodynamics at the interface of classical and quantum physics.

HIGHLIGHTS FROM PHYSICSWEB

Terahertz breakthrough at BESSY

Physicists at the BESSY synchrotron in Berlin have generated a steady-state beam of coherent terahertz radiation for the first time. Synchrotron radiation is produced when bunches of charged particles, usually electrons, are forced to move in circular orbits by magnetic fields. The radiation is often incoherent because the size of the bunches is longer than the wavelength of the radiation they are emitting. However, by operating the electron storage ring of the synchrotron in a special "low-alpha" mode it is possible to make the bunches much smaller and therefore produce a coherent output.

Silver nanoclusters make logic gates

Researchers at Georgia Tech in the US have performed logic operations with a novel optoelectronic device made of silver nanoclusters. The device operates on electronic inputs and produces an optical output that can be read without electrical contacts. The nanoclusters contain between two and eight silver atoms and only emit light when a specific voltage is applied. Devices that rely on an optical read-out can be made much smaller than those that produce electrical outputs.

New structure seen in the Crab pulsar

Radio astronomers have detected sub-pulses lasting for as little as 2 ns within the "giant" pulses emitted by the Crab pulsar. The astronomers believe that the structures responsible for the sub-pulses must be less than 1 m across, which makes them the smallest objects ever to be detected outside the solar system and also the brightest radio sources in the sky.

Lorentz symmetry stays intact

The principle of Lorentz invariance – which states that the result of an experiment is independent of the velocity at which it is performed – is fundamental to the Standard Model of particle physics, but many extensions of the model violate Lorentz invariance. Physicists have now managed to put upper limits on seven of the nine previously unknown coefficients associated with these violations. The experiment involved monitoring a pair of microwave cavities oriented at different angles as the Earth orbited the Sun.

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When photonic crystals meet Fibonacci

Photonic crystals based on the Fibonacci sequence could be the optical chips of the future

From **Jeremy Baumberg** in the Departments of Physics/Electronics and Computer Science, Southampton University, UK

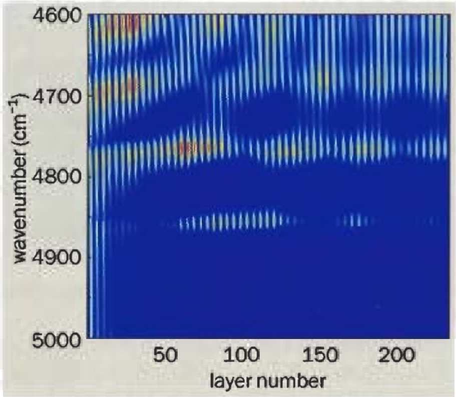
Imagine staring out of your window on a strange scene of warped colours, bent light and regions that are in and out of focus. Either you have mistaken the window for the bottom of a pint glass, or your windowpane could be patterned with a series of nanometre-size holes. When photons strike a transparent solid that is patterned on the scale of the wavelength of light, they scatter at the interfaces and cause multiple interference. This can lead to intriguing optical properties where the normal laws of optics do not apply.

One of the clearest features in a regular, periodic optical crystal is the photonic band gap, which is similar to the electronic band gap a semiconductor. Light in a certain wavelength range simply cannot get through the structure because the photons that are scattered forward by the holes end up cancelling each other out while reinforcing each other in the reflected directions. These band gaps can result in "super-prisms" that drastically split up very similar colours of light, in structures that dramatically reduce the speed of light, and materials with negative refractive indices.

The bizarre effects of photonic crystals can also occur when the scattering structures are random, since the interference can be strong enough to completely localize the light. Now an Italian–Dutch collaboration has found that light can be slowed substantially in photonic structures that are neither regular nor random but quasi-periodic. And not just in any quasi-periodic structure, but one that follows the famous Fibonacci sequence (L Dal Negro *et al.* 2003 *Phys. Rev. Lett.* **90** 55501).

Golden light

The photonic crystals that are most familiar to us are 3D or 1D stacked structures. The iridescence of opal is the result of many stacked layers of submicron glass spheres, and the "cold" windows in some offices are coated with alternating layers of different types of glass that reflect only infrared light. There has also been recent interest in 2D photonic crystals, in which rows of holes are drilled through optical waveguides rather like the nano-drilled windowpane. Majd Zoorob and colleagues at Southampton University recently showed that quasi-periodic 2D patterns have definite band gaps, which is useful because their optical properties are the same for light in every direction.



The light intensity inside the 233 layer Fibonacci crystal (blue indicates low intensity and red indicates high). In the bottom right a band gap can be seen, across which no light can pass.

Luca Dal Negro and co-workers at the universities of Trento, Florence and Amsterdam have now studied an interesting 1D quasi-crystal that is produced by a simple recursion rule – the Fibonacci sequence. Originally uncovered by Leonardo Pisano Fibonacci in 1225 during a mathematical tournament, the Fibonacci sequence solves the topical Australian problem of predicting the number of rabbits there will be after a certain number of months, starting from a single breeding pair. Fibonacci found that the sequence is given by simply adding the two previous terms: 1, 2, 3, 5, 8, 13, 21.... The ratio of successive terms in the Fibonacci sequence tends to the golden ratio, which is about 1.618 – a number that appears throughout nature in other geometrical guises such as seashells, pine cones and cauliflowers.

The researchers built a Fibonacci superlattice from 233 stacks of two optical layers A and B, which were arranged in the sequence BA, ABA, BAABA.... To get the maximum scattering effect, each layer has an optical thickness of one-quarter the wavelength of light. This means that a transmitted beam that is doubly reflected interferes destructively with the direct transmission.

These superlattices also exhibit photonic band gaps, even though they are not periodic (see figure). The optical transmission spectrum of the quasi-crystals becomes very strongly structured as the number of layers is increased. The "breeding" band gaps get closer and closer together, and the colours that can get through become rarer and rarer.

Fibonacci quasi-crystals are particularly useful in understanding the behaviour of light in photonic crystals because they are one of the few structures that can be analysed exactly. Even though the structures are not periodic, the band gaps occur at wavenumbers $k = n\pi/L$, where L is the total thickness of the quasi-crystal and n is an integer set by the Fibonacci sequence. The ratio of successive band-gap frequencies also stabilizes to the golden ratio.

Slowing down

Dal Negro and colleagues have measured how fast light can travel through such states using very short pulses of light that can be tuned in colour around the photonic band gaps. They took photonic videos of the interference of two optical pulses, each with a length of just 100 fs. One was travelling through the quasi-crystal while the other pulse passed through a piece of glass with an equivalent thickness. The videos showed that the speed of the pulses was less than half that expected from the average refractive index of the structure.

The slowing of pulses is quite straightforward to understand. Light travelling through the quasi-crystal gets scattered by an interface between the layers. It then travels in the backward direction before it gets scattered again into the transmitted direction. The average delay that is built up is roughly equal to the product of the number of layers and the optical time period – about 1000 fs for the 233 layer structure used.

But while the ultrashort optical pulses that were used are clearly stretched and delayed, their transmission is extremely low. This trade-off between slowing the pulses down and attenuating them is plaguing researchers who are trying to use the band-edge regions of periodic photonic crystals to delay light pulses in a controlled way. If this could be done successfully it might open the door to information processing and storage in optical chips, as well as telecommunication applications. It could also provide alternative optical devices such as delay lines and highly selective frequency filters. The attenuation problem is already being tackled by various start-up companies such as Mesophotonics in Southampton and Galian Photonics in Vancouver.

Fibonacci quasi-crystals have some promising applications because they confine light in a new way by aperiodic scattering. Using this photon confinement to make very small laser cavities, or combining it with nonlinear layers to make improved optical switches, involves physics that has previously been unconsidered, such as critical localization, where photons are only just trapped by the photonic superlattice. Blending Fibonacci's number theory with Newton's waves leads to very irregular thinking.