bright solitons could be formed, each containing in the region of 6000 condensate atoms (K Strecker *et al.* 2002 *Nature* **417** 150). These multiple-soliton trains were previously known to be possible solutions of the underlying equations that describe Bose–Einstein condensates, but their production is particularly interesting since it allows collisions that are essential to the nature of solitons to be investigated (see figure). Hulet and co-workers observed that the solitons repelled each other, thereby providing information about the phase structure of the underlying condensate wavefunction.

Excitement over excitons

Although quite unrelated, another recent development in Bose–Einstein condensation should be followed with interest. Leonid Butov of the Lawrence Berkeley National Laboratory and co-workers in the US and the UK have recently created regions in a semiconductor that allow the confinement of a high density of composite particles called excitons (L Butov *et al.* 2002 *Nature* **417** 47). This advance is important because it is a precursory step on the way to making a Bose–Einstein condensate from excitons, rather than atoms.

Excitons are created in semiconductors when a laser field promotes an electron from the valance band to the conduction band. The resulting electron in the conduction band and the hole that it leaves behind can form a bound composite object due to the Coulomb attraction. This composite object is the exciton and it can, in principle, undergo Bose–Einstein condensation if the density and temperature are right. Although significant efforts over many years have gone into demonstrating Bose–Einstein condensation of excitons, the results so far have been controversial.

Butov's group was able to demonstrate trapping of excitons in all three dimensions thanks to the development of a semiconductor structure that overcame some of the previous limitations. Sandwiched in the middle of the semiconductor are two layers of quantum wells in which the electrons and holes are created and confined to a 2D world. When an external electric field is applied, an electron can be confined to one of the quantum wells while a hole is trapped in the other, thereby leading to a significant increase in the exciton stability.

Of course, a trap needs to provide confinement in all three dimensions. This was possible because the natural disorder in the system led to random fluctuations in the potential energy. Potential wells a few microns across form at certain places in the material and can confine cold dense clouds of excitons. Although Butov and co-workers have not yet demonstrated Bose–Einstein condensation in this novel system, significant progress has clearly been made.

Breakthroughs galore

These are just two examples of the many exciting developments that are currently going on in this field. In addition, Carl Wieman and colleagues at the JILA laboratory in Colorado have found evidence for a molecular Bose–Einstein condensate in a sample of rubidium-85 molecules (E Donley *et al.* 2002 *Nature* **417** 529; S Kokkelmans *et al.* 2002 arXiv.org/abs/cond-mat/0204504). Rather than cool the molecules, the JILA team converted part of an atomic condensate into molecules by tuning the interactions between the atoms with pulses of magnetic field.

Meanwhile, Wolfgang Ketterle's group at the Massachusetts Institute of Technology has shown that a Bose–Einstein condensate of sodium atoms in an optical trap can be replenished with atoms from a second identical condensate using optical tweezers (A Chikkatur *et al.* 2002 *Science* at press). This advance is an important step towards creating a new type of laser that continually emits atoms rather than photons (see *Physics World* August 1999 pp31–35).

Another goal in condensate research is to observe the transition of a dilute fermion gas to a superfluid phase at relatively high temperatures (see *Physics World* April pp27–31). Such a transition would complement studies of superconductivity in exotic condensed matter, and could shed light on the crossover between normal and high-temperature superconductivity.

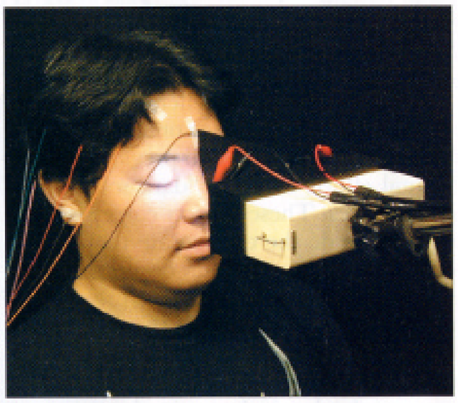
The future for Bose–Einstein condensation is very bright, and if the breakthroughs continue at the current rapid pace, we may not have to wait too long to see what advances it will bring.

Can noise actually boost brain power?

The human brain is the latest biological system to show signs of stochastic resonance

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

Random noise may improve the human brain's ability to process information, according to recent research by two physicists in Japan. Toshio Mori and Shoichi Kai of Kyushu University have shown that the visual-processing region of the human cortex responds better to an external periodic stimulus when external noise is also applied. The findings represent yet another example of the seemingly ubiquitous phenomenon of stochastic resonance – and is one of the most interesting biological examples to date (2002 *Phys. Rev. Lett.* **88** 218101).



Eyes wide shut – electrical signals in the brain respond to light pulses applied to the eyelids.

The notion of stochastic resonance was originally introduced in relation to the Earth's ice-age cycle, in an attempt to explain how a tiny periodic variation in the amount of radiation reaching the surface of the planet could trigger the huge climatic changes that have been discovered. In stochastic resonance, a weak periodic signal in a noisy system can be enhanced by adding extra noise. This astonishing effect was identified about 20 years ago by Roberto Benzi and colleagues at the University of Rome Tor Vergata and, independently, by Katy Nicolis, then at the Belgian Institute for Space Aeronomy in Brussels. Even more remarkably, there are many cases where the signal-to-noise ratio, as well as the signal, is enhanced by the addition of noise.

Stochastic resonance demystified

Although stochastic resonance seemed mysterious at first – and there were even suggestions that it violated the second law of thermodynamics – it was explained in 1990 by Mark Dykman, then at the Ukrainian Academy of Sciences in Kiev. He used classical linear-response theory to point out that stochastic resonance can occur in any noisy system in which the susceptibility is strongly dependent on noise.

In practice there are many such systems, one of the most common being the class of two-state systems or oscillators in which there are two potential wells. In the latter case, the physical origin of the stochastic resonance is intuitively obvious: in the presence of noise, a weak periodic signal can induce coherent hopping between two widely separated states, i.e. the noise produces much larger excursions than would occur without the hopping, thereby amplifying the signal.

There is clearly an optimal noise intensity. With insufficient noise, no hopping takes place, but with too much noise, random hopping occurs frequently and independently of the periodic signal. As the noise intensity increases, the signal at the output rises, passes through a maximum and then decreases again – providing the now well known signature of stochastic resonance. What Dykman showed is that the effect is by no means restricted to two-state systems.

Dykman's picture, which was quickly confirmed by experiment, immediately set stochastic resonance in context within statistical physics. But although the phenomenon became instantly less mysterious, it remained no less remarkable, and examples of stochastic resonance have continued to multiply. Quite apart from the ice-age cycle, the effect is now known to occur in systems as diverse as lasers, electronic circuits, sensory neurons and financial markets. Of course, the fact that it arises in biological systems raises the interesting question of whether they have evolved in order to exploit stochastic resonance to good effect.

Brain teaser

Stochastic resonance has been well demonstrated in the peripheral nervous system and in the cells of sensory organs. For example, Frank Moss and colleagues at the University of Missouri in St Louis have clear evidence for the phenomenon in crayfish and paddlefish.

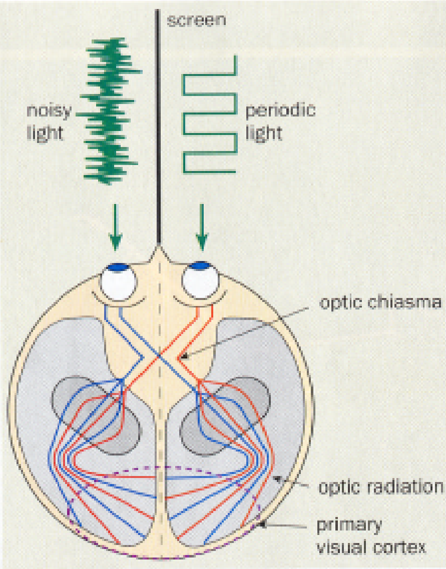
It has also been speculated that stochastic resonance may also arise in the human brain. But it has been difficult to verify this hypothesis because of the challenge of distinguishing between possible stochastic resonance in the brain and possible stochastic resonance in the sensory organs through which the signal and added noise must pass in order to reach the brain.

Mori and Kai have avoided this difficulty by exploiting the particular way in which the eyes are "wired" to the brain. Their experiment uses each of a subject's eyes in different roles: a periodic light signal is applied to one eyelid while a random optical signal (i.e. noise) is applied to the other (figure 1). The way the eyes are wired means that the noise and signal do not interact until they reach the optic chiasma (the point where the left and right optic nerves join) and the visual cortex. In this way, there is no possibility of complications caused by stochastic resonance within the eyes themselves.

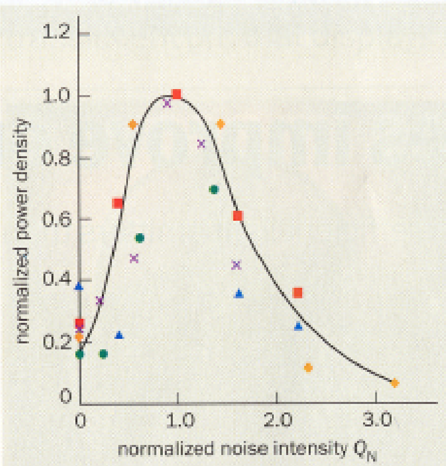
A sufficiently strong periodic visual signal at the right frequency is known to cause neurons to fire in sympathy with the signal over a large area of the brain. Mori and Kai ensured that, in the absence of noise, their signal stimulus was below the threshold needed for this effect to occur.

The Kyushu team detected the brain waves with standard electroencephalograph (EEG) electrodes on the skin and found that a stronger, synchronized response to the signal could be induced by adding noise. Moreover, the EEG signal peaked at a particular noise intensity – the classic signature of stochastic resonance (figure 2). Much the same response was observed in the brains of all five subjects tested and it is very similar in form to results obtained from a diverse range of stochastic-resonance systems.

So, what are we to conclude? Well, stochastic resonance does definitely occur in the human brain, which is an interesting and important result in itself. But the really important questions are whether this remarkable phenomenon occurs naturally in the brain, and whether the brain exploits it in order to enhance its normal information-processing activities. These are far harder questions to answer and will doubtless be the subject of future investigations.



1 In Mori and Kai's experiment, noise enters the left eye and a periodic signal enters the right eye. These inputs induce separate optical neural signals that only come together deep inside the brain.



2 The response of the brain to the periodic signal, as a function of noise intensity Q_N. The different symbols show the response of the different subjects, while the curve is included as a guide.

Highlights from PhysicsWeb

Single photons to soak up data

A technique that measures the orbital angular momentum of single photons could lead to improved performance in quantum cryptography and communication systems. Most quantum-information devices exploit the intrinsic or "spin" angular momentum of photons. However, the spin of a single photon can only have one of two values, whereas its orbital angular momentum can take an infinite number of values. A team of physicists has now shown that it is possible to sort photons into four different orbital-angular-momentum states and thereby encode two bits of information with a single photon.

Lasers propel paper aeroplanes

Japanese physicists have used lasers to power tiny paper aeroplanes to speeds of $1.4\,\mathrm{ms}^{-1}$. When the laser blasted off small amounts of material from aluminium targets on the planes, it produced a reaction force that kept the planes airborne. It might be possible to scale up the technique to make small lightweight aircraft for atmospheric monitoring.

Astronomers find youngest pulsar

The youngest pulsar ever found has been discovered by an international team of astronomers working at the Green Bank Telescope in the US. Pulsars are rapidly spinning neutron stars that are created when giant stars explode at the end of their life. The team believes that PSR J0205+6449 is a mere 820 years old, and that it is the result of a supernova explosion witnessed in 1181. Further observations of the young pulsar will provide new insights into the origins and early evolution of pulsars.

Multi-talented material makes debut

Scientists have developed an organic material that can flip between two stable states with different electrical, optical and magnetic properties. Moreover, the transition temperature can be raised to above room temperature, so the material could be used in a wide range of device applications. The material consists of two phenalenyl ring systems that are connected by a boron atom and chemical groups such as hexyl, butyl or ethyl.

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