

two cerebral hemispheres. The authors used a surgical technique inspired by Gazzaniga's studies of split-brain patients<sup>11</sup> and Mishkin's classic disconnection experiments<sup>12</sup> to sever the connecting fibres (see Fig. 1 on page 699). This meant that each inferior temporal cortex could only 'see' (that is, receive bottom-up inputs from) visual stimuli that appeared in the opposite visual field. The fibres connecting the prefrontal cortices in the two hemispheres were left intact.

When Tomita *et al.* examined the activity of single neurons in an inferior temporal cortex that could not see the cue, this cortex nonetheless reflected the recalled object, albeit with a long latency. The visual information seemed to take a circuitous route, travelling from the opposite inferior temporal cortex (which could see the cue) to the still-connected prefrontal cortices, and then down to the 'blind' inferior temporal cortex. The authors confirmed this pathway by severing the two prefrontal cortices and eliminating the feedback. Sure enough, activity in the inferior temporal cortex was abolished and the monkeys could not complete the task.

Previous studies<sup>13,14</sup> indicated that the prefrontal cortex is involved in recall, but Tomita and colleagues are the first to demonstrate that interactions between the prefrontal and inferior temporal cortices are directly implicated. Like any great experiment, though, the results raise questions. How ubiquitous is the role of the prefrontal cortex in top-down control? For example, is it also involved when we focus our attention on something we anticipate as being informative? By removing top-down signals, we can examine how they interact with bottom-up signals. Some data indicate that top-down signals directly enhance the activity of sensory neurons<sup>15</sup>, but other, less direct, influences are possible. Also, the prefrontal cortex is unlikely to work alone, so the function of other structures will need to be explored.

One of the most exciting things about Tomita and colleagues' study is that it introduces a powerful tool for addressing fundamental questions of cognitive function. Their results also indicate that the prefrontal cortex plays a complicated and central role in brain function. If it exerts such executive control over many brain systems, it is easy to see why damage to the prefrontal cortex produces wide-ranging deficits in functions including memory, attention, selecting behaviours and inhibitory control.

Earl K. Miller is in the Department of Brain and Cognitive Sciences, Center for Learning and Memory, and RIKEN-MIT Neuroscience Research Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA.  
e-mail: ekm@ai.mit.edu

1. Tomita, H., Ohbayashi, M., Nakahara, K., Hasegawa, I. & Miyashita, Y. *Nature* **401**, 699–703 (1999).

2. Nauta, W. J. H. *J. Psychiatr. Res.* **8**, 167–187 (1971).
3. Sakagami, M. & Niki, H. *Exp. Brain Res.* **97**, 423–436 (1994).
4. Asaad, W. F., Rainer, G. & Miller, E. K. *Neuron* **21**, 1399–1407 (1998).
5. Hoshi, E., Shima, K. & Tanji, J. *J. Neurophysiol.* **80**, 3392–3397 (1998).
6. White, I. M. & Wise, S. P. *Exp. Brain Res.* **126**, 315–335 (1999).
7. Fuster, J. M., Bauer, R. H. & Jervey, J. P. *Exp. Neurol.* **77**, 679–694 (1982).
8. Funahashi, S., Bruce, C. J. & Goldman-Rakic, P. S. *J. Neurophysiol.* **61**, 331–349 (1989).

9. Miller, E. K., Erickson, C. A. & Desimone, R. *J. Neurosci.* **16**, 5154–5167 (1996).
10. Fuster, J. M., Bauer, R. H. & Jervey, J. P. *Brain Res.* **330**, 299–307 (1985).
11. Gazzaniga, M. *Neuron* **14**, 217–228 (1995).
12. Mishkin, M. *Phil. Trans. R. Soc. Lond. B* **298**, 83–95 (1982).
13. Hasegawa, I., Fukushima, T., Ihara, T. & Miyashita, Y. *Science* **281**, 814–818 (1998).
14. Rainer, G., Rao, S. C. & Miller, E. K. *J. Neurosci.* **19**, 5493–5505 (1999).
15. Desimone, R. & Duncan, J. *Annu. Rev. Neurosci.* **18**, 193–222 (1995).

### Quantum physics

## Waves, particles and fullerenes

Alastair I. M. Rae

Can the fundamental concepts of quantum physics apply to everyday 'classical' objects as well as those in the atomic and subatomic regime? Can we meaningfully attribute wave properties to an everyday object such as a football, or does quantum theory break down at some level? In one guise or other these questions have been asked ever since the quantum theory was invented.

On page 680 of this issue<sup>1</sup>, Arndt *et al.*, a group working under the direction of Anton Zeilinger in Vienna, report experiments showing that molecules of the fullerene C<sub>60</sub> have wave as well as particle properties, just as predicted by quantum theory. A fullerene

such as C<sub>60</sub> is of course very much smaller than a football, but it does have a mass at least an order of magnitude greater than that of any other object whose wave properties have been previously observed.

There is very little room for doubt concerning the correctness of the wave-particle duality postulate for fundamental particles. About 80 years ago, Prince Louis de Broglie suggested that 'atomic' particles such as electrons had wave as well as particle properties. This received early confirmation from the experiments of Davisson and Germer<sup>2</sup>, which demonstrated electron diffraction for the first time; and the wave properties of neutrons have been exploited for

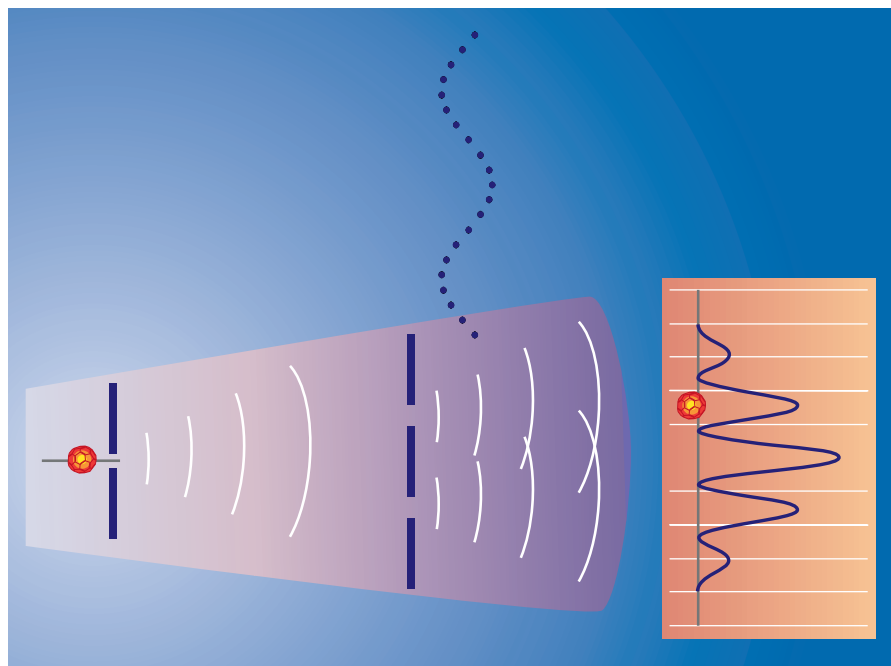


Figure 1 A beam of particles passes through a double slit in the form of a wave and produces an interference pattern. However, whenever the particles are actually detected, their particle properties are manifest. The experiments of Arndt *et al.*<sup>1</sup> demonstrate this effect in the case of C<sub>60</sub> molecules, which are an order of magnitude heavier than anything previously shown to have wave properties. The molecule may absorb or emit radiation while passing through the apparatus, as indicated by the dotted waveform. Provided the wavelength of the radiation is much larger than the distance between the slits, so that it is impossible in principle to tell which slit the molecule passed through, the interference pattern is unaffected.

least 50 years in neutron-diffraction experiments.

An archetypal example of wave-particle duality is the two-slit experiment (Fig. 1). A wave crosses a screen containing two slits. The wave splits it into two parts, which are re-united on a screen, creating an interference pattern. It is the creation of this interference pattern that is an unambiguous signature of a wave. In particular, the fact that the two components cancel each other out at some points in the pattern is very difficult to explain in any other way. On the other hand, when the object reaches the screen it is always detected as a particle — hence the term ‘wave-particle duality’.

Even on the atomic scale, wave-particle duality can raise difficult questions. For example, does the particle actually go through one or other of the two slits or does it in some way exist in both slits simultaneously? We know that if we put detectors into the slits, we will always find that the particle passes through one or other of them; but an essential consequence of such a measurement is that the interference pattern is no longer formed, so that the wave properties are no longer manifest. Results such as these led Niels Bohr to propose that the type of properties (particle or wave, for example) that we are allowed to attribute to a quantum system depend on the type of observation we make on it. Other solutions to this ‘measurement problem’ have been proposed, including the apparently outrageous ‘many worlds’ interpretation in which such a measurement divides the apparatus and everything that interacts with it into two branches that continue to exist, but are for ever unaware of each other’s existence.

A central question in this debate is if and how quantum theory applies to macroscopic objects. Hence the importance of the paper by Arndt *et al.*<sup>1</sup>. For many years Zeilinger’s group has been renowned for its pioneering work in neutron interferometry, but this latest achievement demonstrates the interference of the de Broglie waves associated with molecules of the fullerene C<sub>60</sub>. A molecular beam emerging from an oven at a temperature of 1,000 K is collimated and passed through a grating whose slits are 50 nm wide and 100 nm apart (the use of a grating containing many slits rather than the two-slit interference discussed above introduces no new issues of principle). The emerging beam is detected and found to form an interference pattern that is completely explicable on the basis that the beam has wave properties.

C<sub>60</sub> is of course not a macroscopic object, but it is an order of magnitude more massive than anything else that has been studied in this way before. Being a large molecule at a high temperature, its component atoms are in continual motion and it is an essential requirement for successful interference that these motions remain coherent while the

molecule is passing through the slits. Arndt *et al.* point out that this coherence would be destroyed by any process that would in principle allow an observer to determine through which slit the molecule passed. They calculate that C<sub>60</sub> at this temperature would be expected to emit two or three infrared photons during its passage through the apparatus. But because the wavelength of the radiation associated with these photons is much greater than the distance between neighbouring slits, they carry no information about which slit the molecule passed through and therefore the interference pattern is not affected.

These experiments extend the applicability of wave-particle duality by about one order of magnitude in the macroscopic direction. However there are about 15 orders of magnitude to go before we reach the mass of anything we would normally think of as macroscopic. Some experiments in other fields, such as superconductivity and magnetism (see ref. 3 for review), claim to be demonstrating the quantum properties of

objects with a close-to-macroscopic number of degrees of freedom, but these results are quite controversial. In contrast, the C<sub>60</sub> experiment is quite unambiguous. If it could ever be extended into the genuinely macroscopic regime, the consequences would be profound. If everything can behave like a wave or a particle depending on how it is observed, what does this mean if it includes what we would normally call observers or measuring apparatus, or even the Universe as a whole? If, on the other hand, this is shown to be impossible in principle, we will have reached the point where quantum physics no longer fully applies and the limitations of the most successful theory in the history of physics will have been found. ■

Alastair I. M. Rae is in the School of Physics and Astronomy, University of Birmingham, PO Box 363, Birmingham B15 2TT, UK.

e-mail: a.i.m.rae@bham.ac.uk

1. Arndt, M. *et al.* *Nature* **401**, 680–682 (1999).
2. Davisson, C. J. & Germer, L. H. *Nature* **119**, 558–560 (1927).
3. Chudnovsky, E. M. & Tejada, J. *Cambridge Studies of Magnetism* Vol. 4 (Cambridge Univ. Press, 1998).

## Ecology

# Power behind diversity’s throne

Shahid Naeem

On average, plants contain less than half a gram of carbon per square centimetre. Yet this thin veneer of living matter, a sort of ‘green slime’ sandwiched between a 100-km-deep lithosphere and a 100-km-high atmosphere, manages to cycle 60 gigatonnes ( $60 \times 10^{15}$  g) of carbon per year between the biosphere, lithosphere and atmosphere<sup>1</sup>. Clearly, the Earth’s biota has a staggering capability to affect our environment. But this perspective overlooks a critical feature of plant life; this green slime consists of more than a quarter of a million species. What, if any, is the role of such extraordinary diversity? Is it important to the rates of ecosystem processes? Is it important to the stability of ecosystems? We must answer these questions if we are to understand how widespread losses in biodiversity<sup>2</sup> are likely to affect ecosystem properties and the services they provide<sup>3</sup>. A rapidly growing body of ecological research deals with this issue, and considerable excitement and controversy surround its findings<sup>4</sup>. However, on page 691 Sankaran and McNaughton<sup>5</sup> present results from a very different kind of study that challenges both the nature and the direction of this new field.

Although ranging widely in character and design<sup>6</sup> — from small bottles of microbes<sup>7</sup> to the BIODEPTH experiments that span nine European countries — the flurry of recent experimental work on the role of biodiversity in ecosystem processes

has centred on a single line of investigation. Diversity has been manipulated by constructing replicate ecosystems in which some species are excluded from some replicates. This mimics the biodiversity loss that might arise because of stochastic processes, habitat modification, overexploitation, displacement by invasive species or other processes that result in the local extirpation of species<sup>8</sup>.

Although local extirpation of species is perhaps the most visible and disturbing cause of contemporary declines in biodiversity, Sankaran and McNaughton examine whether large-scale variation in diversity is actually caused by factors such as climate, the frequency of disturbance, soil fertility and other factors known as extrinsic determinants of diversity. That is, unlike most experiments, which measure ecosystem properties across a gradient in diversity generated by extirpation, these authors measured ecosystem response to perturbation across an existing gradient of diversity generated by extrinsic determinants. Specifically, they selected three types of savanna grassland in India’s Western Ghat Mountains that varied in diversity due to extrinsic determinants (most likely disturbance), then perturbed replicate plots by clipping, burning or both. The authors measured resistance stability — how much a system changes after perturbation — a widely studied and important property of ecosystems.