

behaviour. The authors conclude that pre-mating isolation has a diffuse genetic basis.

Doi *et al.*², meanwhile, studied isolation between the cosmopolitan *D. ananassae* (A) and its Melanesian sibling species *D. pallidosa* (P). These species are almost completely sexually isolated. But the authors show that A females no longer discriminate strongly against P males if the males are prevented from singing their 'love songs' (by removal of their wings) or if females are prevented from hearing them (by removal of their 'ears'). This suggests that divergence in male song patterns and associated female preferences underlies the sexual isolation (and speciation) in this case.

First-generation female hybrid offspring of A and P flies showed the same pattern of discrimination as A females, implying that the A genes involved are dominant over the P genes. Most of these genes mapped to chromosome II and, remarkably, repeated backcrossing revealed that only a single chromosomal region, marked by the *Delta* gene, was required for hybrids to prefer A males. So, a small locus — perhaps even a single dominant allele — might underlie the preference of A females for A males. Surprisingly, this region did not affect the readiness of A females to mate with P males. Perhaps the preferences for A and P males have a different genetic basis, or perhaps the gene (or genes) in the region marked by *Delta* controls willingness to mate rather than preference.

There are some caveats to the single-gene interpretation. The *Delta*-containing region might be larger (and so include more genes) than the authors suspect; characterization of more molecular markers in this region will help here. Nonetheless, if a single gene could be identified and cloned, it would be a significant addition to the poor list of speciation genes. At the moment, we really have no idea what a 'preference' gene might be like. Another question is whether genes that influence male song map to the same region.

The conclusions of the two studies^{1,2} are strikingly different — a fact that may be related to variations in behavioural complexity. It seems that the divergence of acoustic signals alone explains the isolation between the A and P species², whereas the behavioural basis of mate choice in the M and Z forms involves many types of signal¹⁰. The differences in experimental design may have accentuated this effect: Doi *et al.* measured the likelihood of A females accepting A or P males, but did not offer a choice, whereas Ting *et al.* measured relative mating success in a multiple-choice design.

Alternatively, the different genetic architectures may reflect the histories of these populations. The M and Z forms seem to have diverged while in the same areas, but the A and P species may have evolved while geographically separate. Ting *et al.* suggest that the M and Z forms of *D. melanogaster*

might not be able to evolve to the point at which they are separate species because too many genes are involved in sexual isolation. With such different patterns apparent in the few studies available, many more systems will have to be analysed before a really informative picture emerges. ■

Roger Butlin is at the School of Biology, University of Leeds, Leeds LS2 9JT, UK. e-mail: r.k.butlin@leeds.ac.uk

Michael G. Ritchie is at the School of Biology, University of St Andrews, St Andrews KY16 9TS, UK.

e-mail: mgr@st-and.ac.uk

Quantum physics

Air juggling and other tricks

Eric J. Heller

Quantum tunnelling breaks the rules of classical physics — and leads to ghost-like transfer of matter through barriers. Demonstrations of a new type of quantum tunnelling have the ghosts taking new liberties.

An old joke goes like this: a motorist stops to ask a farmer how to get to a village a few miles away. After much thought, the farmer says with conviction: "You can't get there from here."

The farmer may have been a classical physicist. Given constraints such as energy conservation, certain types of motion are isolated in classical systems — one type never leads to the other. Usually we think of a hill or energy barrier preventing the journey, but often the barriers are more subtle and indirect. Imagine a ball bouncing between two semicircular mirrors (Fig. 1). Classical dynamics forever confines it to the region between the mirrors, even though there is no energy barrier preventing it leaving through one of the open gaps. Classical motion does not allow escape, but quantum mechanics is famous for allowing tunnelling into classically forbidden barriers, and even right through them.

Can quantum systems wriggle out of subtler, dynamical barriers like those presented by the two mirrors? Absolutely. Delicate experiments in the Phillips laboratory¹ (described on page 52 of this issue), and in the Raizen laboratory² (published by *Science*), demonstrate 'dynamical tunnelling'^{3–5} of ultracold atoms, which allows them to transfer between two stable, but classically separate, states of motion.

Dynamical tunnelling is a close cousin of 'above-barrier reflection', in which a particle with enough energy to go over a barrier is nonetheless reflected back — an event forbidden by classical physics. This is also sometimes called diffraction, but this term is used in so many contexts (some of them classically forbidden, some not) that it is best avoided. Dynamical tunnelling can have remarkable

1. Ting, C.-T., Takahashi, A. & Wu, C.-I. *Proc. Natl Acad. Sci. USA* **98**, 6709–6713 (2001).
2. Doi, M., Matsuda, M., Tomaru, M., Matsubayashi, H. & Oguma, Y. *Proc. Natl Acad. Sci. USA* **98**, 6714–6719 (2001).
3. Dobzhansky, T. *Genetics and the Origin of Species* (Columbia Univ. Press, New York, 1937).
4. Tan, C. C. *Genetics* **31**, 558–573 (1946).
5. Wu, C.-I. & Palopoli, M. F. *Annu. Rev. Genet.* **23**, 283–308 (1994).
6. True, J. R., Weir, B. S. & Laurie, C. C. *Genetics* **142**, 819–837 (1996).
7. Ting, C.-T., Tsaur, S. C., Wu, M. L. & Wu, C.-I. *Science* **282**, 1501–1504 (1998).
8. Ritchie, M. G. & Phillips, S. D. F. in *Endless Forms: Species and Speciation* (eds Howard, D. A. & Berlocher, S.) 291–308 (Oxford Univ. Press, Oxford, 1998).
9. Hollocher, H. *et al. Evolution* **51**, 1175–1181 (1997).
10. Colegrave, N., Hollocher, H., Hinton, K. & Ritchie, M. G. *J. Evol. Biol.* **13**, 143–150 (2000).

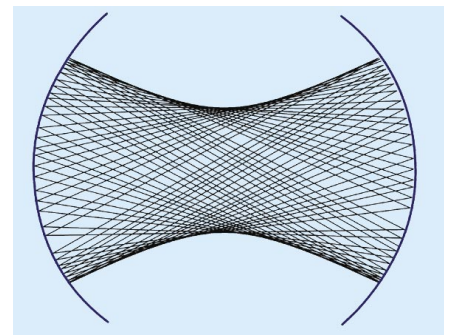


Figure 1 Classical and quantum motion of a bouncing ball. Two semicircular mirrors confine a bouncing ball to a regular pattern of motion. Even though escape is possible energetically, and no potential barrier would prevent it, the classical motion of the ball does not allow it to escape. Quantum mechanically, it would be able to slowly escape, by 'dynamical tunnelling'. This sort of quantum tunnelling has been discussed theoretically, and has now been observed directly in experiments^{1,2} with ultracold atoms trapped in laser fields.

and non-intuitive consequences. Consider the formaldehyde molecule, H₂CO, spinning about the C–O axis with the oxygen atom pointing up (Fig. 2, overleaf). Classically, the oxygen is doomed to point up forever, but in quantum mechanics it can oscillate between pointing up and down. It does this without violating the conservation of energy or angular momentum. In reality, a rotating formaldehyde molecule that starts with oxygen pointing up does flip its direction, just as predicted by quantum mechanics.

By using relatively large numbers of atoms, the Phillips and Raizen groups^{1,2} have caught extremely cold quantum gases in the act of doing something impossible for

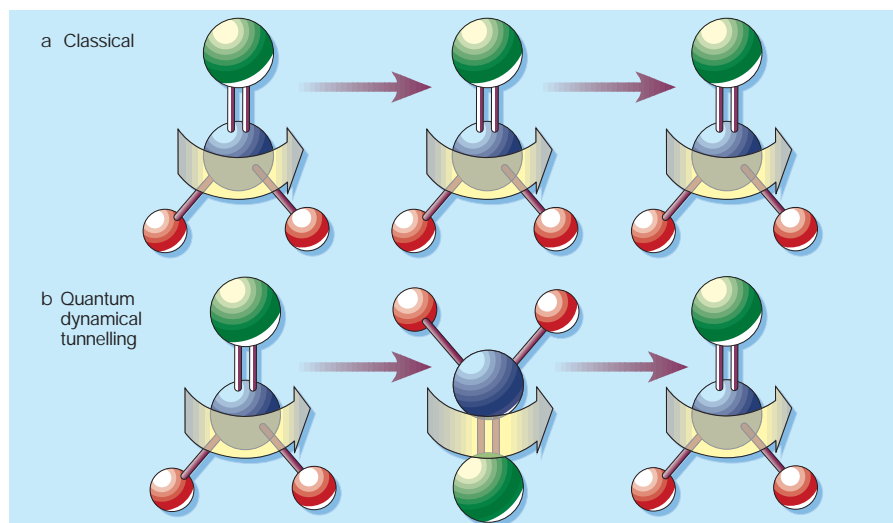


Figure 2 Classical and quantum motion of a formaldehyde molecule. **a.** In the classical picture, a rotating H_2CO molecule always stays in the same orientation, with the oxygen atom pointing upwards. **b.** In the quantum picture, the H_2CO molecule can flip between an oxygen-up and an oxygen-down state through a process known as dynamical tunnelling.

classical particles. The atoms were put into a very distinct kind of motion, but were later seen in the wrong place at the wrong time (if they had continued to behave classically). Specifically, they were caught travelling in the wrong direction — a feat that is possible only if they had used dynamical tunnelling to get there. Classical particles would need a specific kick to change their direction.

The two groups of experimentalists used a web of crossed laser beams to create elaborate three-dimensional force fields in which the intensity of the light varies periodically. This sort of 'optical lattice' was first created in the early 1990s. When ultracold atoms are added to the lattice they are attracted or repelled from regions of strong laser intensity, depending on the colour (frequency) of the laser beams, which are kept far from an atomic absorption frequency. By varying the strength of the laser light, the experimentalists can control the positions and motions of the atoms. The result is like a juggling act, in which the balls (atoms) are kept in motion in space by precise forces exerted at just the right time.

But the juggling acts performed by the Phillips¹ and Raizen² groups have a twist. Imagine an identical juggler standing next to the first one. He is 'air juggling' — that is, he has nothing to juggle with and is just going through the motions. The first juggler does not throw his balls to him, but even so the second juggler finds that after a time he has the balls, and the first becomes the air juggler. And then the first juggler has the balls again, and so on. This is dynamical tunnelling. The Raizen group achieved it with thousands of atoms, and the Phillips group with millions of atoms in a Bose–Einstein condensate, a form of matter in which all the atoms have the same quantum state.

But what is happening at that magical

halfway point, when the balls have not completely tunneled from one juggler to the other? At this point, the balls are in both places at once with equal probability — a feature known as quantum coherent superposition, and an essential ingredient of any approach to building quantum computers, for example. So the demonstration of dynamical tunnelling is also a demonstration of quantum coherent superposition of distinct events — all of the atoms were travelling in both directions at once. This is a fact of life in the quantum realm.

Both experimental groups worked with systems containing a degree of chaotic motion, which makes things more challenging theoretically. They did not do this deliberately — the moving optical field they created with the laser beams induces regions of classical chaos. But it raised the possibility that the process leading to the atoms going the wrong way was classical chaotic motion, rather than quantum tunnelling. Chaos is an aspect of classical systems that corresponds to extreme sensitivity to initial conditions, and often

leads to rapid, seemingly random cycling between different kinds of motion. At the suggestion of Vitali Averbukh of the Technion in Israel, the Phillips group took pains to rule out the possibility that classical chaotic transport was heavily involved, thereby confirming that dynamical tunnelling was taking place.

These experiments also raise the possibility of an even newer tunnelling concept — chaos-assisted tunnelling⁶. Chaos can coexist with regions of stable, non-chaotic motion because some types of motion, called regular motion, can avoid getting mixed up in the chaotic fray. In this regime, chaos can assist tunnelling by providing a 'free ride' over to another zone of regular motion once the system has tunneled out of the first regular zone into the chaotic region.

Many previous experiments have demonstrated quantum tunnelling by individual atoms or molecules, but a nearly macroscopic system containing millions of atoms might be expected to behave more classically. Certainly near-macroscopic tunnelling has been seen before, as in the Josephson effect in superconductors or in barrier tunnelling by Bose–Einstein condensates⁷, but such observations are rare, and physicists are always hungry for more examples. From a broader perspective, these and other recent experiments demonstrate that it is possible to exert quantum control over ultracold atoms with astonishing finesse and coherence. We can look forward to a continuing stream of mind-bending examples, perhaps leading to a better understanding of the implications of quantum mechanics. ■

Eric J. Heller is in the Departments of Physics and Chemistry, Harvard University, Cambridge, Massachusetts 02138, USA.

e-mail: heller@physics.harvard.edu

1. Hensinger, W. K. *et al.* *Nature* **412**, 52–55 (2001).
2. Steck, D. A., Raizen, M. G. & Oskay, W. H. *Science* **5 July 2001** (10.1126/science.1061569).
3. Davis, M. J. & Heller, E. J. *J. Chem. Phys.* **75**, 246 (1981).
4. Davis, M. J. & Heller, E. J. *J. Phys. Chem.* **85**, 307 (1981).
5. Lawton, R. T. & Child, M. S. *Mol. Phys.* **44**, 709–723 (1981).
6. Tomsovic, S. & Ullmo, D. *Phys. Rev. E* **57**, 1421 (1998).
7. Anderson, B. P. & Kasevich, M. A. *Science* **282**, 1686–1689 (1998).

Ecology

Price put on biodiversity

Oswaldo E. Sala

The greater the plant diversity in an ecosystem, the greater the ecosystem's productivity. A new analysis indicates that the higher productivity results from complementary patterns of species resource use.

Human activities are drastically altering Earth's biodiversity. To get a handle on what the consequences might be, ecologists have been busily carrying out experiments. But interpreting such experiments has been confounded by the possible opera-

tion of two different causal mechanisms, with contrasting implications. This matter is tackled by Loreau and Hector on page 72 of this issue¹. They have devised a way of teasing apart the two effects, drawing upon a formulation — the Price equation — used