Quantum physics

How long does quantum tunnelling take?

Alessandro Fedrizzi & Fabio Biancalana

Measurements with confined photons challenge a prediction that particles that 'quantum tunnel' into infinitely long barriers will get stuck. **See p. 67**

This year is the International Year of Quantum Science and Technology, marking the centenary of the development of quantum mechanics. Quantum mechanics makes accurate predictions at the atomic and subatomic scales, but physicists are still debating how the equations of quantum theory should be interpreted. On page 67, Sharoglazova *et al.*[1] tested an alternative to the standard interpretation of quantum theory by measuring how long it took photons to perform a quantum phenomenon called tunnelling. This alternative interpretation, called Bohmian mechanics, predicts that tunnelling causes quantum particles to be stationary inside infinitely long barriers, but the researchers' findings challenge this theory.

When a classical (non-quantum) object such as a ping-pong ball hits a wall, it rebounds. Quantum particles, by contrast, sometimes 'tunnel' into a potential barrier (a region with higher potential energy than the surroundings) even if their kinetic energy is lower than would be required by classical physics. Quantum tunnelling explains natural processes such as radioactive decay and some types of enzyme catalysis. It also powers instruments such as scanning tunnelling microscopes, which use tunnelling to image surfaces on an atomic scale. However, physicists still don't know how long quantum tunnelling takes.

In quantum mechanics, objects are described by a function called the wavefunction, which captures the wave-like nature of matter at the quantum scale. The wavefunction gives the probability of finding a particle in a given region of space and time. In this framework, time, unlike other system properties, cannot be observed. Instead, it is an external parameter that must be inferred relative to something else. For example, tunnelling times have been measured using a property of atoms called spin[2]. However, it is difficult to make testable predictions of tunnelling times using standard quantum mechanics.

In many interpretations of quantum mechanics, particles do not have specific positions in the wavefunction, and it is difficult to predict where and when they will appear in an experiment. But in the Bohmian interpretation[3], particles are point-like, and their positions are determined by 'hidden' variables that physicists cannot currently measure. The particles are guided along definite trajectories by a 'pilot wave', which is part of the wavefunction. From these trajectories, the particles' velocities and time spent inside a barrier can be calculated. Sharoglazova *et al.* designed an experiment to test a prediction of the Bohmian interpretation: that a particle that tunnels into an infinitely long barrier is at rest, so the time it spends in the barrier, which is called the dwell time, is infinite.

The researcher's experiment was the quantum equivalent of a ball rolling down a ramp and colliding with a wall. For the 'ball', the researchers used photons generated by shining a laser into a thin layer of liquid that contained fluorescent dye molecules. The liquid was sandwiched between two mirrors, and the confinement made the photons behave like particles that have mass[4].

The bottom mirror was modified to create two parallel channels, or 'waveguides', that the photons could move along (Fig. 1). The primary waveguide was nanostructured to create a ramp, on which the photons were generated. The initial position of the photons on the ramp determined their potential energy, and this could be set by moving the laser. Photons travelled down the ramp and along the primary waveguide until they reached a barrier. This barrier was long enough for it to seem infinite to a tunnelling photon. The more

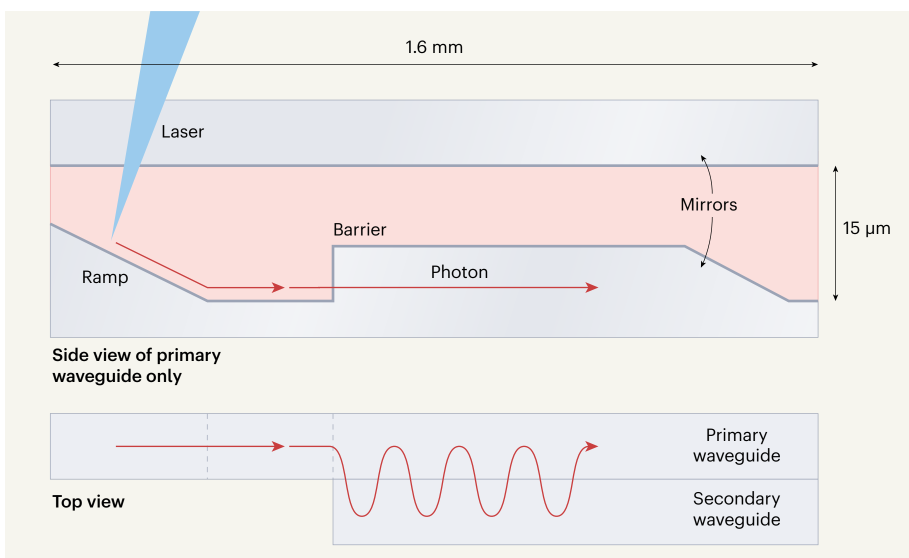

Figure 1 | A quantum tunnelling experiment. Quantum tunnelling allows quantum particles to travel into regions of space, called barriers, that would be forbidden by classical physics. Sharoglazova *et al.*[1] measured the speed of photons tunnelling into a barrier. The experiment took place in a dye-filled cavity between two mirrors. The bottom mirror was nanostructured to create two 'waveguides' that directed the light. In the primary waveguide, photons were generated by shining a laser at fluorescent dye molecules. This waveguide formed a ramp that gave the photons potential energy. The photons travelled down the ramp until they encountered a barrier. When they tunnelled into the barrier, they also tunnelled sideways into the secondary waveguide. The rate at which the photons hopped between the two waveguides was used to measure the speed of the particles in the barrier.

potential energy the photons started with, the higher their kinetic energy when they reached the barrier. The researchers used photons that had different energies, both above and below the classical threshold for a particle to travel into the barrier.

Sharoglazova and colleagues measured time by making the tunnelling particles oscillate with a known frequency. In the barrier, the waveguides ran parallel to each other, and were positioned so that as photons tunnelled through the barrier, they also tunnelled sideways, hopping back and forth between the waveguides. The rate of this hopping is a well-defined property of such systems, and could be measured. The oscillation of the particles therefore acted as a clock.

Some of the photons were transmitted through the top mirror and were captured by a camera. The researchers used the images to obtain the relative population of photons at various points along the two waveguides. From this, they calculated the speed of the tunnelling particles.

When a particle tunnels into a barrier, its kinetic energy is lower than the potential energy of the barrier, which means that its local kinetic energy is negative. This energy was calculated for each run of the experiment from the initial position of the photons.

The researchers showed that the more negative the kinetic energy of the particles, the faster they travelled inside the barrier. The transmission of light through the mirrors meant that the number of effective particles in the waveguides decreased with distance into the barrier. The speed and rate of population decay of the particles were used to calculate a characteristic distance and dwell time. Sharoglazova and colleagues' dwell times were finite, challenging the Bohmian prediction that particles inside an infinite barrier have infinite dwell times.

The speed of the particles was used to predict how long they would take to tunnel through a finite barrier. These predictions matched experimental[2] and theoretical[5,6] findings, validating the method. However, it is unlikely that Sharoglazova and colleagues' results will resolve the debate over the validity of the Bohmian interpretation. Their experiment relies on a series of sophisticated assumptions that might be open to challenges. For example, the equation that determines the time evolution of the wavefunction applies to massive particles, but the researchers' experiment was an analogue that used massless photons that behaved like massive particles.

Furthermore, there are no definite, testable predictions of dwell times made with standard quantum mechanics against which the Bohmian predictions can be tested (it has even been argued that such predictions cannot exist[7]). This makes it difficult to rule out the Bohmian interpretation, because it might be adapted in light of the new results. Nevertheless, Sharoglazova and colleagues' experiment adds a rare empirical data point to a discourse that, until now, has been mostly confined to theory.

Alessandro Fedrizzi and **Fabio Biancalana** are in the School of Engineering & Physical Sciences, Heriot-Watt University, Edinburgh EH14 AS, UK.
e-mails: a.fedrizzi@hw.ac.uk; f.biancalana@hw.ac.uk

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Ageing

A bile acid links calorie restriction to longevity

David A. Sinclair

Could lithocholic acid, a compound produced when gut bacteria process bile, be the missing link between a low-calorie diet and its age-defying effects? Experiments in mice, flies and nematode worms provide clues. **See p.192 & p.201**

Across the ancient world, physicians from Greece to China touted the health benefits of bile and fasting. Today, the focus is on regular meals and exercise, but perhaps those ancient doctors were onto something. In two papers in *Nature*, Qu and colleagues[1,2] make a compelling case that a component of bile called lithocholic acid (LCA) triggers many of the age-defying and potentially lifespan-extending health benefits of low-calorie diets.

First, some background on calories, ageing and bile acids. Low-calorie diets were formally shown to delay ageing in the early twentieth century, when researchers fed rats a mix of food and indigestible cellulose[3]. Since then, calorie restriction has been shown to prolong lifespan in several species, although some mouse strains and wild-derived animals show minimal or even negative responses to calorie restriction[4], and in rhesus monkeys (*Macaca mulatta*) the effects have been mixed, for reasons that are debated[5].

At first, the benefits of calorie restriction were attributed to delayed development or slowed metabolism, but in the 2000s, a new paradigm emerged: that calorie restriction triggers a genetically encoded survival mechanism. This concept came to light after the discovery of alterations in single genes that extended lifespan in model organisms, ostensibly by mimicking calorie restriction and environmental threats to survival[6–8].

Generally speaking, bile is less interesting than is longevity, but that might soon change. Consisting mainly of water, bilirubin (a breakdown product of haemoglobin), cholesterol and bile acids, this yellow-green fluid is synthesized in the liver, stored in the gallbladder and released into the small intestine to emulsify dietary fats and increase the absorption of fat-soluble vitamins. Gut-resident bacteria, such as species of *Clostridium* and *Lactobacillus*, convert primary bile acids into the secondary bile acids deoxycholic acid and LCA, some of which is reabsorbed into the bloodstream.

Previous work has identified bile acids as health-promoting compounds. Dafachronic acids, which are structurally related to LCA, extend the lifespans of nematode worms (*Caenorhabditis elegans*)[9] and LCA extends the lifespans of yeast (*Saccharomyces cerevisiae*) and fruit flies (*Drosophila melanogaster*; see ref. 10 and references therein). In mammals, LCA is not known to extend lifespan, but it does alter physiology in ways that are consistent with improved health, such as lowering levels of liver triglycerides, blood glucose and systemic inflammation — in part, by activating the bile-acid receptor TGR5 (ref. 11). LCA is also implicated in the lifespan-extending effects of transplanting gut microbiota from young mice into old mice, but how the bile acid might impart health benefits is unclear[12].

In mammals, a family of seven enzymes known as sirtuins (or SIRT1–7) combat numerous biological processes that contribute to ageing, including cellular senescence (in which cells stop dividing), DNA damage, decreased energy production and impaired tissue repair. Their reactions require the ubiquitous metabolite molecule NAD^+, the levels of which