Center, 2333 CR Leiden, the Netherlands, and in the Department of Life Sciences, Imperial College London, UK.
e-mails: mattf@earth.ox.ac.uk; martin.brazeau@gmail.com

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QUANTUM PHYSICS

Watching the wavefunction collapse

The continuous random path of a superconducting system's quantum state has been tracked as the state changes during measurement. The results open the possibility of steering quantum systems into a desired state. SEE LETTER P.211

ANDREW N. JORDAN

Continuous quantum measurements of a system gently interrogate the state of the system. The usually abrupt collapse of the wavefunction, which generally occurs upon measurement, happens gradually over a period of time. Advances in superconducting quantum systems now permit scientists to track a single 'quantum trajectory' describing the continuous random path a quantum state takes as it collapses from a quantum superposition into one of its classically permitted states. Writing in this issue (page 211), Murch *et al.*[1] report an experiment that both confirms the theory of quantum trajectories and develops a way to quantum control in solid-state systems.

The past decade has seen tremendous technological development in the area of superconducting quantum systems. Research on quantum measurements and control of single systems has until recently been dominated by the field of quantum optics, which deals with photons and atoms[2]. However, techniques to fabricate man-made atoms in the form of superconducting systems — which display discrete energy levels and the long quantum coherence times that are critical for making many operations on the systems before they become effectively classical objects — have steadily produced longer coherence times. In 2000, the typical coherence times of such superconducting quantum systems were 10 nanoseconds, whereas today the times are in excess of 100 microseconds, a 10,000-fold increase[3].

Murch and colleagues' experiment uses a relatively new kind of system called a three-dimensional transmon[3]. This system is a superconducting element that is described by a ground (lowest-energy) state and a first excited state, and is kept at a low temperature. The quantum state of the system can be detected by putting the superconducting element inside a microwave box. The detector works in a similar way to the microwave ovens sitting in many kitchens. Microwaves are sent into the box, and interact with the superconducting system. A kitchen microwave causes water molecules to quickly rotate and bump into their neighbours, so that the microwaves are absorbed and energy is directly transferred to heat the water in food.

By contrast, the superconducting transmon is fixed in place, and the microwaves are far off being in resonance with the frequency needed to drive the system between its ground and excited states, so no absorption occurs. This causes an indirect interaction between the microwave photons and the quantum system. The microwaves come back out of the box through a separate port, and the information about the quantum system is read out from a shift in phase (where a wave's peaks and troughs lie) that the waves undergo in the box. This is possible because the physics of the interaction between the microwaves and the superconducting system is well understood, and can be used to calibrate the output to tell which state the system is in.

An important element of this experiment is

Figure 1 | Of butterflies and quantum trajectories. Murch and colleagues[1] performed measurements on a quantum system that enabled them to track the continuous random path, or quantum trajectory, of the system's state as it collapsed to a final state during the measurement process. Here, measurements starting from the same initial state will realize a different quantum trajectory, eventually ending in the quantum system's ground or excited state. The process is analogous to watching butterflies that make their way, one by one, across a field from a cage to one of two nearby trees (the ground and excited states in this analogy). Each butterfly's flight pattern is like a single run of the experiment.

that it takes time to fully measure the system. Although there is information about the quantum system in the outcoming microwaves, it is only a small amount of information. This is because the microwave photons exhibit quantum noise that masks the system contribution. Such a situation is sometimes called a weakly responding detector[4] and the underlying measurements are called weak measurements[5]. Consequently, only after collecting a sufficient amount of data can one distinguish the system signal from the noise and reliably determine the system's final collapsed state.

During the process of data collection, the authors use the quantum-trajectories formalism to infer the state of the quantum system from the continuous stream of microwaves. This formalism recognizes that the process of collecting data is continuous, and therefore uses the information contained in the weak measurement to update the quantum state in light of the new information received. The fact that there is very little knowledge gained about the system in the data means that the disturbance to the system is small, so the updated state is close to the original state. This process is then repeated as more data are collected, which generates the quantum trajectory, where the state follows a diffusive motion in time. Thus, Murch and colleagues literally watch the wavefunction continuously collapse to a final state in a single experimental run.

The method of following the quantum state in time is similar to chasing butterflies released from a cage (Fig. 1). Suppose each butterfly flies in a random zig-zag pattern, but eventually makes its way across a field to land on one of two trees. If another butterfly is released with the same initial conditions, it follows a different zig-zag path. Consequently, it is not possible to predict the flight pattern of the butterfly. However, after watching enough butterflies make the journey, one can make statistical predictions about questions such as: which tree will it land on? How long will the journey take? What will the average path be, given it lands on the first tree? In the same way, although an individual quantum trajectory is a random process, similar statistical questions can be asked, such as: what is the probability that the system will end up in the excited state? What is the average time it takes to get there? What will the average quantum trajectory be, given that it ends in the excited state[6]? One of the theoretical predictions successfully checked in this work is that the quantum trajectory at a given time depends only on the total integrated detector signal up to that point in time.

When a butterfly is chased, it will alter its path in response to being pursued, opening the possibility of steering the butterfly to where you want it to go. Similarly, the fact that quantum trajectories can be monitored suggests the possibility of steering them through the use of feedback control — in which control parameters of the quantum system are dynamically changed in response to the measurement outcome. Indeed, this same research group has already published the results of an experiment implementing such control to stabilize the dynamics of a continuously measured system[7].

The published data also show the effect of measurement uncollapse in continuous measurements[8,9]. Because the detector gives only partial information about the quantum state, there is the possibility that the detector output 'reverses its judgement' about the state of the system. The authors noticed that there were several times when the quantum trajectory returned the state back to where it started. The detector measured the system for some time, partially collapsing the system's state, and then measured again for some time, uncollapsing it.

This experiment further cements solid-state systems as a central player in the manipulation and control of single quantum systems, the area of the 2012 Nobel Prize in Physics, awarded to Serge Haroche and David Wineland[10]. It opens the way to further investigations in quantum feedback and control, and it exhibits the fundamental importance of new ideas in weak and continuous quantum measurement, a field that has until recently been largely ignored in solid-state physics, but now seems to have an upward 'trajectory'. ■

Andrew N. Jordan *is in the Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA, and at the Institute for Quantum Studies, Chapman University, Orange, California 92866, USA.*
e-mail: jordan@pas.rochester.edu

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MICROBIOLOGY

RNAs at fever pitch

Some normally innocuous bacteria can turn into serious pathogens. It seems that one such species, *Neisseria meningitidis*, uses three RNA-based thermosensors to escape the immune response of its human host. SEE LETTER P.237

FRANZ NARBERHAUS

The flow of genetic information, from DNA to RNA to protein, is strictly controlled, such that only a subset of genes is actively expressed under any given condition. Contact between a bacterium and a mammalian host elicits profound changes in bacterial gene expression to adjust to the new conditions and to escape detection by the host's immune system. But what host cellular parameters are monitored, and at what level does gene regulation occur? On page 237 of this issue, Loh *et al.*[1] report that *Neisseria meningitidis* registers increasing temperature as an alarm signal that indicates the risk of an inflammation-activated immune system*. They show that the bacterium uses three different temperature-sensing RNA molecules to coordinate processes involved in evading this immune response.

Neisseria meningitidis (often referred to as meningococcus) is the leading cause of septicaemia and meningitis in young children and adolescents. Paradoxically, it is a harmless commensal (resident) bacterium found in the nasopharynx of many individuals. The triggers that can lead this microorganism to enter the bloodstream and cross the blood–brain barrier, and the mechanisms by which it achieves this while escaping immune detection, are only partially understood.

To identify factors involved in these processes, Loh and collaborators screened for mutant *N. meningitidis* strains that were able to survive repeated exposure to human serum, which contains immune-defence molecules. Five out of the six resistant strains that they identified were characterized by the loss of an identical sequence of eight nucleotide bases lying in front of a genetic region involved in synthesizing the capsule — a protective polysaccharide layer that surrounds the bacterial cell.

How can such a short genetic deletion prevent killing by the immune system? The authors found that all five strains produce elevated levels of the capsule-synthesis enzyme CssA. Assuming that the deletion would destroy the recognition site for a transcription factor, they tested 38 such proteins for involvement in regulating this genetic region. None of them was involved.

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