QUANTUM MECHANICS

No moon there

An experiment reveals that micrometre-sized superconducting circuits follow the laws of quantum mechanics, and thus defy common experience of how macroscopic objects should behave.

Johan E. Mooij

"I like to think that the moon is there even if I don't look at it", Albert Einstein once remarked. He objected to the notion that truly macroscopic objects might behave according to the laws of quantum mechanics, and thus be subject to the same uncertainties as photons or spins. In 1985, in a paper[1] entitled 'Quantum mechanics versus macroscopic realism: is the flux there when nobody looks?', Anthony Leggett and Anupam Garg provided the script for a quantitative test to determine whether a macroscopic object would indeed at all times be in one of its distinct two states or whether quantum mechanics would prevail. The example they used was that of a superconducting ring generating a measurable magnetic flux. Twenty-five years on, writing in *Nature Physics*, Agustin Palacios-Laloy and colleagues[2] now report an experimental realization of the Leggett–Garg test. Using a superconducting circuit similar to the one proposed originally, they show that the behaviour of their 'macroscopic object' clearly follows the predictions of quantum mechanics. The moon — a small moon, admittedly — is not there.

Quantum mechanics has very successfully been used, for example, to explain the structure of atoms or to understand the behaviour of electrons in solid materials. But there is a deeper side to quantum mechanics, where the mathematical formulation of its laws leads to consequences that run counter not only to intuition but also to common sense. One such consequence is the entanglement of two quantum objects that are placed at distant locations — measurements on one object can lead to seemingly impossible consequences for the outcome of measurements on the other[3]. Such consequences have convincingly been demonstrated in experiments since the early 1980s, both with photons and atoms[4,5]. In these experiments, 'local realism' is broken; there seems to be some kind of 'hidden' communication between the two local measurements. John Bell in 1964 formulated quantitative criteria in the form of inequalities[6], which are used for specific testing of these mysterious aspects of quantum mechanics.

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The painting *New Moon Eclipsed* by Rob Gonsalves is an example of an art style called magic realism, where detailed realistic representation is combined with elements that defy common sense. Intricate measurements on a superconducting circuit[2] reveal on analysis that time correlations are stronger than would be possible in a macroscopic realistic world, in agreement with predictions of quantum mechanics.

Leggett and Garg were similarly ahead of their time. They foresaw the possibility of macroscopic objects that behave according to quantum mechanics. The prototype for their thought experiment[1] was a superconducting ring that supports two states of circulating supercurrent of opposite sign, and the starting points of their study were the concepts of macroscopic realism and of non-invasive measurement. Common sense would dictate these to be valid for large objects — macroscopic realism requires that the system is in one of its two states at all times, whereas a non-invasive measurement leaves the object in the state it occupied before the readout. From these simple premises, Leggett and Garg derived inequalities pertaining to correlations between consecutive measurements on a single macroscopic object. A quantum object would violate the inequality. Therefore, the Leggett–Garg inequality is often referred to as a Bell's inequality in time.

Palacios-Laloy *et al.*[2] describe measurements on a superconducting circuit where the Leggett–Garg inequality is violated, thus favouring quantum mechanics over macroscopic realism. Their circuit is not the simple loop that Leggett and Garg had in mind[1], but a different superconducting quantum two-level system. Palacios-Laloy *et al.* employ a so-called transmon[7,8], which is a combination of a Cooper-pair transistor that senses the individual superconducting charge carriers (that is, the Cooper pairs) and a high-quality superconducting oscillator operating at 5.8 GHz. Making use of the transmon's long coherence times, Palacios-Laloy *et al.* continuously drive transitions between its ground and excited state with a microwave signal. The resulting dynamics — commonly known as Rabi oscillations — is similar to that of spins in magnetic-resonance systems. Measurements on the state of the transmon are performed by reflecting a second resonant microwave signal off the oscillator and continuously measuring the induced phase shift.

With their scheme, Palacios-Laloy *et al.* implemented a continuous 'weak' measurement. Education in quantum mechanics traditionally focuses on fully projective readout, consistent with the practice in quantum optics that a photon detector either clicks or not, in a ratio proportional to the quantum probability of a photon being there. The presence of that detector has no influence before it is used. The detector for superconducting circuits, in contrast, tends to be at least partly connected in a permanent way to the system to be probed. This leads easily to backaction. When the coupling is weak, the backaction is lower but the measurement is weak as well. The concept of weak measurements has not enjoyed much attention so far, but it is potentially very powerful. The detector that has its connection to the outside classical world becomes part of the experiment. A small amount of information can be used in real time to influence the quantum processes. Such 'quantum feedback' can be useful for quantum information processing but could also be incorporated, for example, in very delicate measurements of mechanical oscillations and be an aspect of detectors for gravity waves.

Over the past decade, progress in research on quantum circuits has been remarkable, in particular with superconducting circuits. Quantum information processing based on quantum optics with single photons and with single atoms or ions is in general still far ahead when it comes to the fidelity of operations and readout. But the gap is narrowing and the stage is reached where solid-state circuits are used to perform experiments that are not so easily done with photons or atoms. The coupling of a superconducting two-level quantum system to a high-quality resonator can be made very strong, and controlled photon states in cavities have been realized with superconducting qubits[9]. The experiment of Palacios-Laloy *et al.*[2] is a new example of this trend.

Research that had the work of John Bell[6] as its central guiding principle has led to important applications in quantum communication and computation. The Leggett–Garg inequality might offer similar surprises of its own. ❐

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BIOPHYSICS

Green quantum computers

In photosynthesis, the Sun's energy is harvested and converted into biomass, greening the planet. Evidence is growing that quantum mechanics plays a part in that process. But exactly how, and why, remains to be explored.

Gregory D. Scholes

Do quantum effects have a role in nature? Can quantum mechanics help explain biological processes, and can biological systems in turn serve as inspiration in our quest to build a quantum computer? In a step towards answering such questions, Mohan Sarovar and colleagues[1], writing in *Nature Physics*, predict that entanglement — a defining quantum property and central element of quantum information processors — can be found in photosynthetic proteins after they absorb light.

In the photosynthetic systems of plants, algae and some bacteria, several proteins work together to capture the Sun's energy and convert it to chemical energy[2]. The scale of photosynthesis on Earth is astounding. Across the globe, the process generates approximately 105 billion tons of biomass per year — this means that, on average, biomass worth twice the mass of the Great Pyramid of Giza is produced every hour. It is not surprising, therefore, that photosynthesis has shaped our atmosphere and impacts our climate. In their study of the role that quantum mechanics may play in photosynthesis, Sarovar *et al.*[1] examine a protein called the Fenna–Matthews–Olson (FMO) complex, one of the players in the tightly orchestrated and complex machinery found in green sulphur bacteria. The special role of the FMO complex in these photosynthetic bacteria is to wire energy between the two key modules of the machinery (Fig. 1). One is a light-harvesting protein, a vast antenna for capturing sunlight and storing its energy transiently as electronic excited states in molecules such as chlorophyll (think of them as electron waves dancing in the confines of a molecule). The