KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

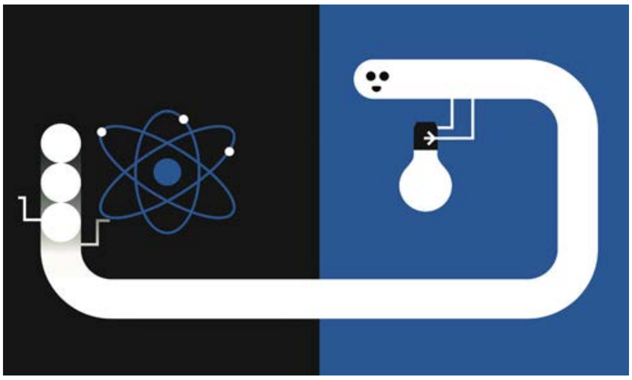
THE NOBEL PRIZE IN PHYSICS 2025

POPULAR SCIENCE BACKGROUND

Quantum properties on a human scale

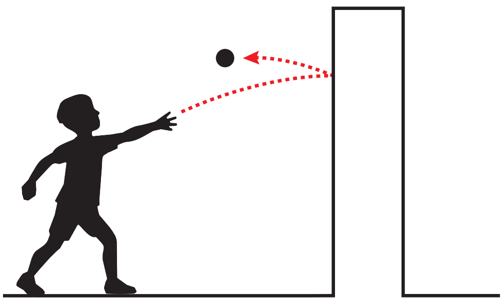
*The Nobel Prize Laureates in Physics for 2025, **John Clarke**, **Michel H. Devoret** and **John M. Martinis**, used a series of experiments to demonstrate that the bizarre properties of the quantum world can be made concrete in a system big enough to be held in the hand. Their superconducting electrical system could tunnel from one state to another, as if it were passing straight through a wall. They also showed that the system absorbed and emitted energy in doses of specific sizes, just as predicted by quantum mechanics.*

A series of groundbreaking experiments

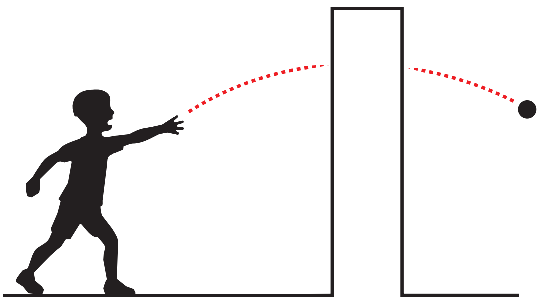


Quantum mechanics describes properties that are significant on a scale that involves single particles. In quantum physics, these phenomena are called *microscopic*, even when they are much smaller than can be seen using an optical microscope. This contrasts with *macroscopic* phenomena, which consist of a large number of particles. For example, an everyday ball is built up of an astronomical amount of molecules and displays no quantum mechanical effects. We know that the ball will bounce back every time it is thrown at a wall. A single particle, however, will sometimes pass straight through an equivalent barrier in its microscopic world and appear on the other side. This quantum mechanical phenomenon is called *tunnelling*.

This year's Nobel Prize in Physics recognises experiments that demonstrated how quantum tunnelling can be observed on a macroscopic scale, involving many particles. In 1984 and 1985, John Clarke, Michel Devoret and John Martinis conducted a series of experiments at the University of California, Berkeley. They built an electrical circuit with two superconductors, components that can conduct a current without any electrical resistance. They separated these with a thin layer of material that did not conduct any current at all. In this experiment, they showed that they could control and investigate a phenomenon in which all the charged particles in the superconductor behave in unison, as if they are a single particle that fills the entire circuit.



When you throw a ball at a wall, you can be sure it will bounce back at you.



You would be extremely surprised if the ball suddenly appeared on the other side of the wall. In quantum mechanics this type of phenomenon is called tunnelling and is exactly the type of phenomenon that has given it a reputation for being bizarre and unintuitive.

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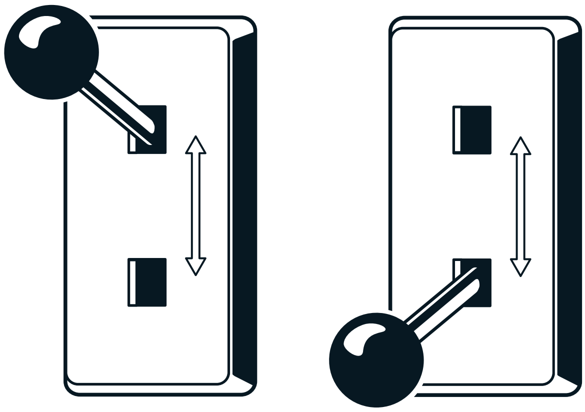
This particle-like system is trapped in a state in which current flows without any voltage – a state from which it does not have enough energy to escape. In the experiment, the system shows its quantum character by using tunnelling to escape the zero-voltage state, generating an electrical voltage. The laureates were also able to show that the system is quantised, which means it only absorbs or emits energy in specific amounts.



Initially, the experiment has no voltage at all. It is as if there is a lever in the off position, and something is blocking from being moved to on. Without the effects of quantum mechanics, this state would remain unchanged.

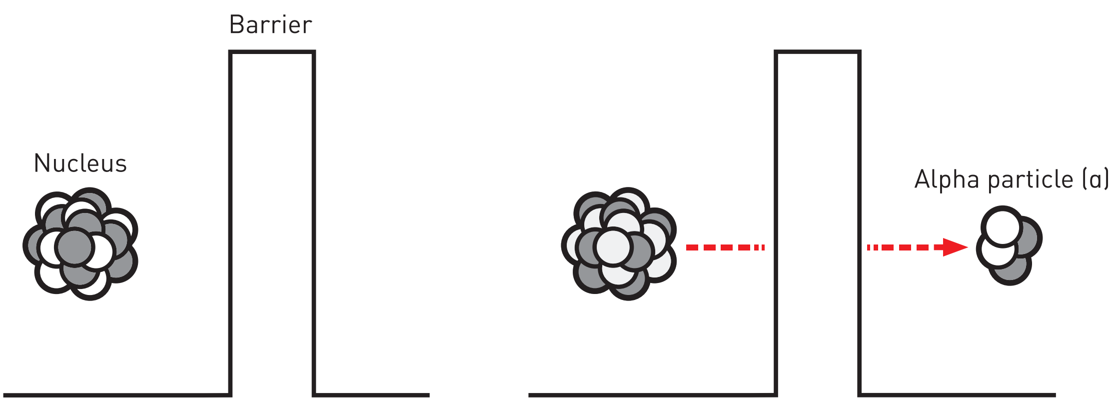
Suddenly, a voltage appears. This is as if the lever has moved from off to on, despite the barrier between the two. What happened in the experiment is called macroscopic quantum tunnelling.

Tunnels and crossings

To help them, the laureates had concepts and experimental tools that had been developed over decades. Together with the theory of relativity, quantum physics is the foundation of what has come to be called modern physics, and researchers have spent the last century exploring what it entails.

Individual particles' ability to tunnel is well known. In 1928, the physicist George Gamow realised that tunnelling is the reason why some heavy atomic nuclei tend to decay in a particular manner. The interaction between the forces in the nucleus creates a barrier around it, holding in the particles it contains. However, despite this, a small piece of the atomic nucleus can sometimes split off, move outside the barrier and escape – leaving behind a nucleus that has been transformed into another element. Without tunnelling, this type of nuclear decay could not occur.

Tunnelling is a quantum mechanical process, which entails that chance plays a role. Some types of atomic nuclei have a tall, wide barrier, so it can take a long while for a piece of the nucleus to appear outside it, while other types decay more easily. If we only look at a single atom, we cannot predict



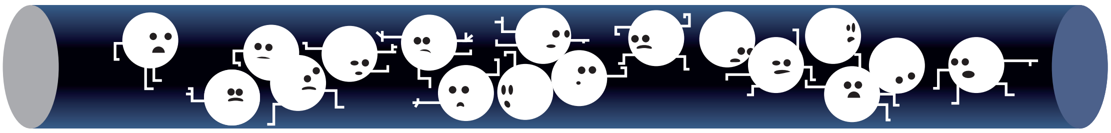
Physicists have known for almost a century that tunnelling is necessary for a particular type of nuclear decay (alpha decay). A tiny piece of the atom's nucleus breaks free and appears outside it.

when this will happen, but by watching the decay of a large number of nuclei of the same type, we can measure an expected time before tunnelling occurs. The most common way of describing this is through the concept of half-life, which is how long it takes for half the nuclei in a sample to decay.

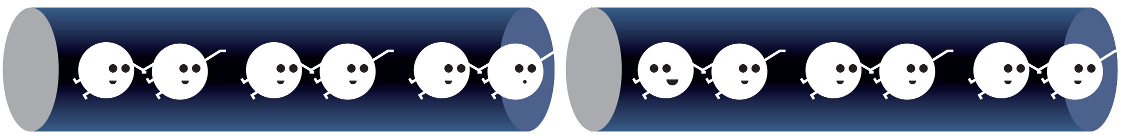
Physicists were quick to wonder whether it would be possible to investigate a type of tunnelling that involves more than one particle at a time. One approach to new types of experiments originated in a phenomenon that arises when some materials get extremely cold.

In an ordinary conductive material, current flows because there are electrons that are free to move through the entire material. In some materials, the individual electrons that push their way through the conductor may become organised, forming a synchronised dance that flows without any resistance. The material has become a superconductor and the electrons are joined together as pairs. These are called Cooper pairs, after Leon Cooper who, along with John Bardeen and Robert Schrieffer, provided a detailed description of how superconductors work (Nobel Prize in Physics 1972).

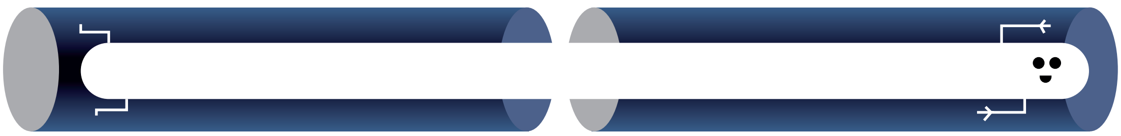
Cooper pairs behave completely differently to ordinary electrons. Electrons have a great deal of integrity and like to stay at a distance from each other – two electrons cannot be in the same place if they have the same properties. We can see this in an atom, for example, where the electrons divide themselves into different energy levels, called shells. However, when the electrons in a superconductor join up as pairs, they lose a bit of their individuality; while two separate electrons are always distinct, two Cooper pairs can be exactly the same. This means the Cooper pairs in a superconductor can be described as a single unit, one quantum mechanical system. In the language of quantum mechanics, they are then described as a single *wave function*. This wave function describes the probability of observing the system in a given state and with given properties.



In a normal conductor, the electrons jostle with each other and with the material.



When a material becomes a superconductor, the electrons join up as pairs, *Cooper pairs*, and form a current where there is no resistance. The gap in the illustration marks the Josephson junction.



Cooper pairs can behave as if they were all a single particle that fills the entire electrical circuit. Quantum mechanics describes this collective state using a shared *wave function*. The properties of this wave function play the leading role in the laureates' experiment.

If two superconductors are joined together with a thin insulating barrier between them, it creates a Josephson junction. This component is named after Brian Josephson, who performed quantum mechanical calculations for the junction. He discovered that interesting phenomena arise when the wave functions on each side of the junction are considered (Nobel Prize in Physics 1973). The Josephson junction rapidly found areas of application, including in precise measurements of fundamental physical constants and magnetic fields.

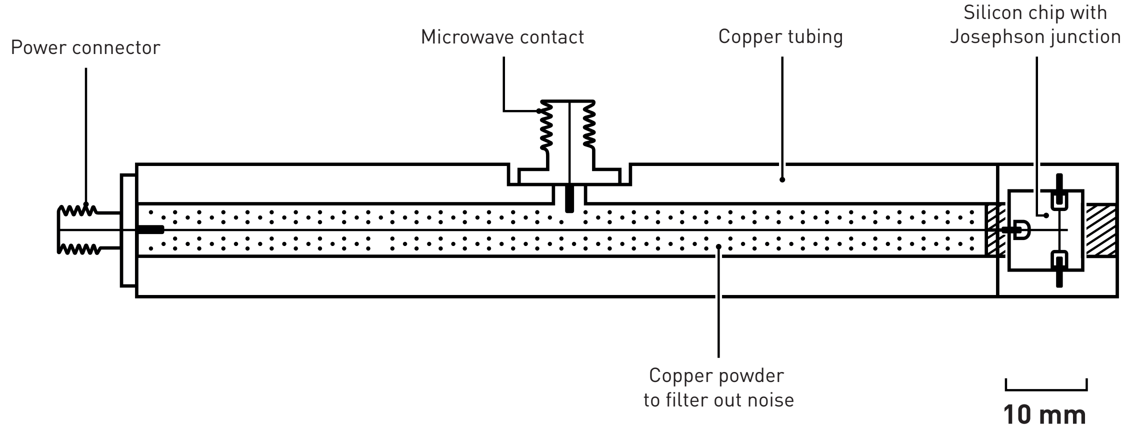
The construction also provided tools for exploring the fundamentals of quantum physics in a new way. One person who did so was Anthony Leggett (Nobel Prize in Physics 2003), whose theoretical work on macroscopic quantum tunnelling at a Josephson junction inspired new types of experiments.

The research group starts its work

These subjects were a perfect match for John Clarke's research interests. He was a professor at the University of California, Berkeley, in the US, where he had moved after completing his doctoral degree at the University of Cambridge, UK, in 1968. At UC Berkeley he built up his research group and specialised in exploring a range of phenomena using superconductors and the Josephson junction.

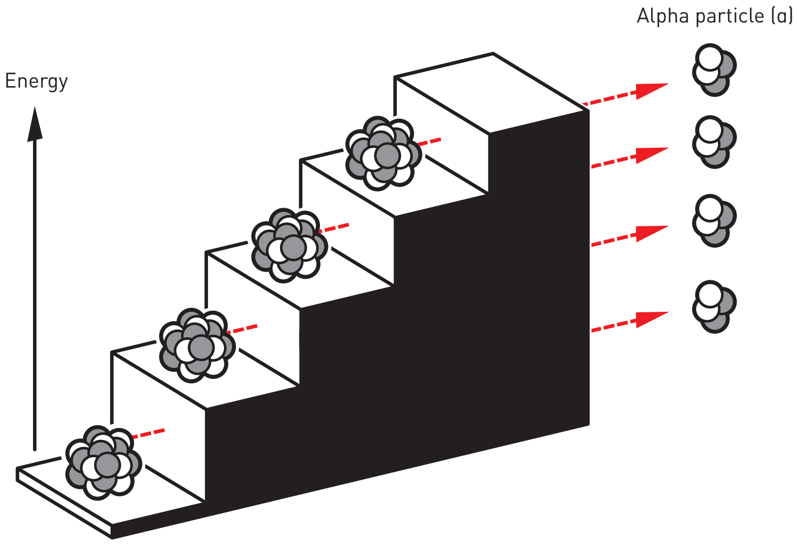
By the mid-1980s, Michel Devoret had joined John Clarke's research group as a postdoc, after receiving his doctorate in Paris. This group also included the doctoral student John Martinis. Together, they took on the challenge of demonstrating macroscopic quantum tunnelling. Vast amounts of care and precision were necessary to screen the experimental setup from all the interference that could affect it. They succeeded in refining and measuring all the properties of their electrical circuit, allowing them to understand it in detail.

To measure the quantum phenomena, they fed a weak current into the Josephson junction and measured the voltage, which is related to the electrical resistance in the circuit. The voltage over the Josephson junction was initially zero, as expected. This is because the wave function for the system is enclosed in a state that does not allow a voltage to arise. Then they studied how long it took for the system to tunnel out of this state, causing a voltage. Because quantum mechanics entails an element of chance, they took numerous measurements and plotted their results as graphs, from which they could read the duration of the zero-voltage state. This is similar to how measurements of the half-lives of atomic nuclei are based on statistics of numerous instances of decay.



John Clarke, Michel Devoret and John Martinis constructed an experiment using a superconducting electrical circuit. The chip that held this circuit was about a centimetre in size. Previously, tunnelling and energy quantisation had been studied in systems that had just a few particles; here, these phenomena appeared in a quantum mechanical system with billions of Cooper pairs that filled the entire superconductor on the chip. In this way, the experiment took quantum mechanical effects from a microscopic scale to a macroscopic one.

The tunnelling demonstrates how the experimental setup's Cooper pairs, in their synchronised dance, behave like a single giant particle. The researchers obtained further confirmation of this when they saw that the system had quantised energy levels. Quantum mechanics was named after the observation that the energy in microscopic processes is divided into separate packages, quanta. The laureates introduced microwaves of varying wavelengths into the zero-voltage state. Some of these were absorbed, and the system then moved to a higher energy level. This showed that the zero-voltage state had a shorter duration when the system contained more energy – which is exactly what quantum mechanics predicts. A microscopic particle shut behind a barrier functions in the same way.



A quantum mechanical system behind a barrier can have varying amounts of energy, but it can only absorb or emit specific amounts of this energy. The system is quantised. Tunnelling occurs more easily at a higher energy level than at a lower one so, statistically, a system with more energy is held captive for less time than one with less energy.

Practical and theoretical benefit

This experiment has consequences for the understanding of quantum mechanics. Other types of quantum mechanical effects that are demonstrated on the macroscopic scale are composed of many tiny individual pieces and their separate quantum properties. The microscopic components are then combined to cause macroscopic phenomena such as lasers, superconductors and superfluid liquids. However, this experiment instead created a macroscopic effect – a measurable voltage – from a state that is in itself macroscopic, in the form of a common wave function for vast numbers of particles.

Theorists like Anthony Leggett have compared the laureates' macroscopic quantum system with Erwin Schrödinger's famous thought experiment featuring a cat in a box, where the cat would be both alive and dead if we did not look inside. (Erwin Schrödinger received the Nobel Prize in Physics 1933.) The intention of his thought experiment was to show the absurdity of this situation, because the special properties of quantum mechanics are often erased at a macroscopic scale. The quantum properties of an entire cat cannot be demonstrated in a laboratory experiment.

However, Legget has argued that the series of experiments conducted by John Clarke, Michel Devoret and John Martinis showed that there are phenomena that involve vast numbers of particles which together behave just as quantum mechanics predicts. The macroscopic system that consists of many Cooper pairs is still many orders of magnitude smaller than a kitten – but because the experiment measures the quantum mechanical properties that apply to the system as a whole, for a quantum physicist it is fairly similar to Schrödinger's imaginary cat.

This type of macroscopic quantum state offers new potential for experiments using the phenomena that govern the microscopic world of particles. It can be regarded as a form of artificial atom on a large scale – an atom with cables and sockets that can be connected into new test set-ups or utilised in new quantum technology. For example, artificial atoms are used to simulate other quantum systems and aid in understanding them.

Another example is the quantum computer experiment subsequently performed by Martinis, in which he utilised exactly the energy quantisation that he and the other two laureates had demonstrated. He used a circuit with quantised states as information-bearing units – a *quantum bit*. The lowest energy state and the first step upward functioned as zero and one, respectively. Superconducting circuits are one of the techniques being explored in attempts to construct a future quantum computer.

This year's laureates have thus contributed to both practical benefit in physics laboratories and to providing new information for the theoretical understanding of our physical world.

FURTHER READING

Additional information on this year's prizes, including a scientific background in English, is available on the website of the Royal Swedish Academy of Sciences, *www.kva.se*, and at *www.nobelprize.org*, where you can watch video from the press conferences, the Nobel Lectures and more. Information on exhibitions and activities related to the Nobel Prizes and the Prize in Economic Sciences is available at *www.nobelprizemuseum.se.*

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2025 to

JOHN CLARKE

Born 1942 in Cambridge, UK. PhD 1968 from University of Cambridge, UK. Professor at University of California, Berkeley, USA.

MICHEL H. DEVORET

Born 1953 in Paris, France. PhD 1982 from Paris-Sud University, France. Professor at Yale University, New Haven, CT and University of California, Santa Barbara, USA.

JOHN M. MARTINIS

Born 1958. PhD 1987 from University of Californa, Berkeley, USA. Professor at University of California, Santa Barbara, USA.

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

Science Editors: Ulf Danielsson, Göran Johansson and Eva Lindroth, the Nobel Committee for Physics
Text: Anna Davour
Translation: Clare Barnes
Illustrations: Johan Jarnestad
Editor: Sara Gustavsson
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