

NOBEL PRIZE IN PHYSICS 2025: BRINGING QUANTUM TUNNELING ALL THE WAY UP TO THE HUMAN SCALE

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Quantum mechanics and quantum superpositions govern the microscopic world. However, when systems get bigger and bigger, eventually quantum tunneling becomes more and more elusive, until it becomes unobservable at human scales. Or so it was thought.

This year's Nobel Prize celebrates breakthrough experiments showing how, by designing specific systems that are strongly decoupled from the environment, quantum tunneling can be stabilized in systems big enough for humans to observe. This fundamental science discovery, originally a purely blue-sky research question without immediate applications at the time, paved the way for a wide range of modern technologies, including a variety of current quantum technologies.

An important initial question is, why do quantum superposition and tunneling disappear as we make objects bigger? The fundamental reason is that any object is coupled to its environment, and quantum superpositions are, in general, very fragile to it. If we start in a quantum superposition state, the dynamics with the environment quickly make the system collapse to one of the classical states. The key to bringing quantum superpositions all the way up relies on engineering systems that, due to an intrinsic protection, get exceptionally decoupled from the environment.

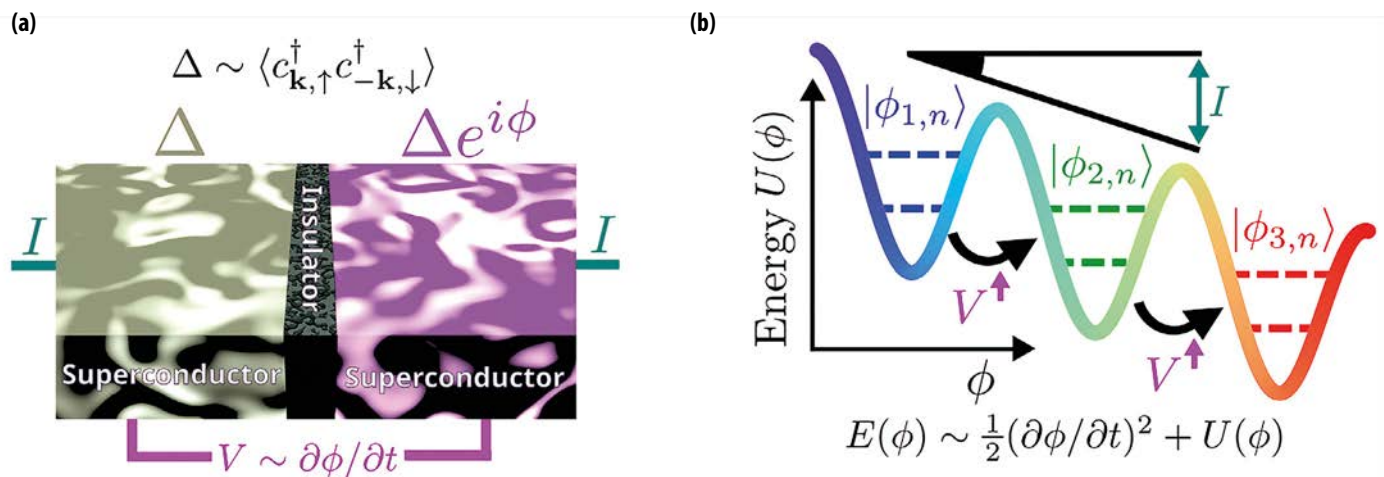
A specific type of quantum material that represents a promising starting point for this is superconductors. In superconducting materials, the whole set of active electrons forms a single collective wavefunction through the formation of a condensate of Cooper pairs. The formation of this collective wavefunction is accompanied by the opening of an energy gap in the system, meaning that a superconducting material requires a finite amount of energy to be driven away from its quantum collective state. This is, among others, why superconductors are a crucial building block of many quantum technologies. The superconducting wavefunction thus becomes a macroscopic example of a collective quantum state. However, a question remains: how can we use superconducting

quantum materials to actually observe quantum tunneling at macroscopic scales?

The key strategy is to leverage two superconductors that are weakly coupled, instead of one. Each superconductor will have its own collective quantum wavefunction, having a relative phase with respect to one another (Fig. 1a). The phase difference between two superconductors has an important consequence, which is the appearance of a current between them. Moreover, if we put a voltage between the two superconductors, this gives rise to a change in the phase between them in time. The combination of these two effects can be rationalized by reinterpreting that the phase difference between superconductors is an effective particle, which is governed by a time-dependent differential equation. Most importantly, the phase difference between superconductors

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▲ FIG. 1: (a) Schematic of two weakly coupled superconductors, where the collective wavefunction of the system has a phase difference between the left and right one. This relative phase, associated with a macroscopic collective wavefunction, becomes an effective macroscopic quantum mechanical quasiparticle. The energy landscape (b) of this phase quasiparticle features a tilted set of valleys, where the tilting is controlled by the current. The valleys lead to quantum mechanical level quantization, that can feature tunneling between levels in different valleys. At the lowest temperatures, the appearance of tunneling between states, observable electrically as a voltage spike, is only possible through macroscopic quantum tunneling of the collective quantum state.

is in itself a quantum mechanical variable, and therefore it is governed by a quantum mechanical equation, rather than a classical one. This motivated the following question: Is it possible to observe the quantization of that phase variable and the quantum tunneling between different states?

At finite temperatures, a classical particle in a valley can escape if it is able to extract energy from the environment, a process enabled by having a finite temperature, and climb over the barrier. If the phase particle overcomes the barrier, a sudden voltage switch is observed. As the temperature is lowered, such events become rarer and rarer. Eventually, at zero temperature, if the particle were purely classical, overcoming the valley is forbidden. However, for a quantum mechanical particle, tunneling between states is possible (Fig. 1b), even when approaching zero temperature, for which the tunneling rate would become constant. By tracking the rate as a function of temperature, it was revealed that at the lowest temperatures, the barrier climbing is dominated by quantum tunneling, instead of thermal activation. Furthermore, by using a microwave resonator, it was demonstrated that the phase particle had a set of quantized levels, which could be selectively observed as if they were a large-scale artificial atom.

Bringing quantum tunneling to macroscopic scales requires systems that conserve their quantum mechanical nature as they are scaled all the way up. Superconductors were one of the earliest examples, yet most importantly, now many other examples exist.

This includes entangled photons, thanks to their weak coupling to the environment, macroscopic mechanical resonators, thanks to exceptionally high quality factors, and topological fractional materials, thanks to collective topological protection. Most importantly, while these platforms are interesting in themselves, they could be connected, enabling the transfer of quantum superpositions from charge to optical to mechanical macroscopic quantum states. The search for macroscopic quantum states is a race to out-engineer nature, overcoming the natural mechanisms leading to decoherence by exploiting exceptionally fine-tuned, intrinsically protected, and controlled devices. Macroscopic tunneling in superconductors represents now the basis of many ongoing technologies, ranging from neuroimaging techniques, superconducting quantum computers, to qubit-based quantum detectors. Bringing quantum superposition to macroscopic scales further presses on some of the most fundamental open questions, including what happens in devices where gravitational forces can be measured in a quantum superposition state, or can we reach quantum superposition at human scales and temperatures?

The discovery of macroscopic quantum tunneling is a paradigmatic example of how a purely fundamental question has now become a cornerstone of a wide range of technologies. This demonstration of new fundamental phenomena opens a new door, opening up a wide range of possibilities, enabling technologies that we could not consider before. Macroscopic quantum tunneling, demonstrated 40 years ago, has now become a key pillar of our current quantum technology. Fundamental discoveries happening now, and happening in the next few years, will be the future pillars of our future technologies, pillars that we are not able to imagine what they will be, giving rise to technologies whose consequences we cannot foresee. And ultimately, that will provide us with currently unimaginable tools that may enable us to tackle fundamental, technological, and global challenges that right now we perceive as impossible to overcome. ■