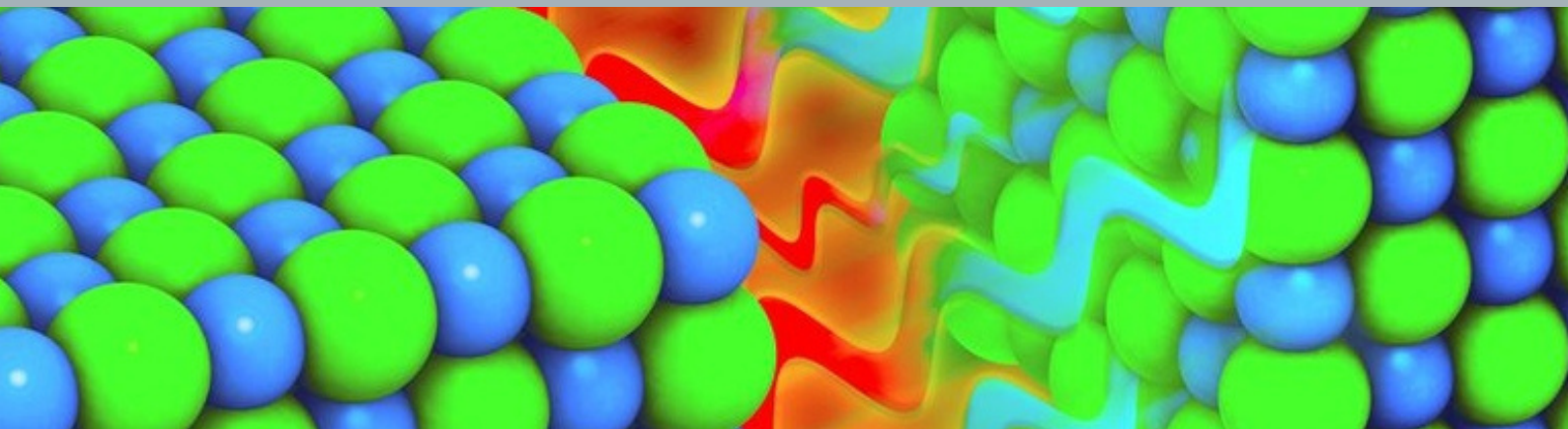




2025 Nobel Prize in Physics: Tunnelling into the Quantum Frontier

“THE DISCOVERY OF MACROSCOPIC QUANTUM MECHANICAL TUNNELLING AND ENERGY QUANTISATION IN AN ELECTRIC CIRCUIT”,



QUANTUM TUNNELLING

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The Nobel Prize for Physics this year will be awarded to three scientists — John Clarke, Michel Devoret and John Martinis, the Royal Swedish Academy of Sciences said on Tuesday. The three worked together and devised experiments to tease greater insight into the workings of the quantum world: the realm of the ultra-small when objects, broken down to single, constituent particles, cease to behave in the way we ordinarily expect them to. One of the mind-boggling behaviours that particles are capable of here is “tunnelling”, literally, the ability of particles to pass through physical walls.

What is Quantum Tunnelling?

- Quantum tunnelling is a quantum mechanical phenomenon where a particle passes through a potential energy barrier that it classically should not have enough energy to overcome. This occurs because particles in quantum mechanics have wave-like properties, and their wavefunctions can extend beyond barriers, giving a finite probability that the particle can "tunnel" through to the other side, even when classical physics says it should be confined by the barrier.
- This effect cannot be explained by classical mechanics, as it involves the particle appearing on the far side of a barrier without physically climbing over it. Quantum tunnelling is crucial in many natural phenomena, such as radioactive decay and nuclear fusion in stars, and it underpins modern technologies like quantum computing, tunnel diodes, and scanning tunneling microscopes.
- The phenomenon emerges from the wave nature of matter and the uncertainty principle that allows particles to exist in probabilistic states, enabling them to penetrate barriers of about a few nanometers in thickness. Recently, quantum tunnelling has also been observed at macroscopic scales in superconducting circuits, showing quantum mechanics applies to larger systems as well.

- In essence, quantum tunnelling allows particles to bypass classical energy restrictions due to their dual wave-particle nature, making it a fundamental concept in quantum physics with both theoretical and practical significance.

Key Applications of Quantum Tunneling

- **Scanning Tunneling Microscope (STM):** STM uses quantum tunneling of electrons between a sharp metal tip and a surface to image surfaces at atomic resolution, enabling observation and manipulation of individual atoms.
- **Nuclear Fusion:** Quantum tunneling allows atomic nuclei in stars, which don't have enough energy to overcome the Coulomb barrier classically, to fuse and release energy, facilitating stellar nuclear fusion processes.
- **Alpha radioactive decay:** This process, where an atomic nucleus spontaneously emits an alpha particle, was one of the earliest successes for quantum tunneling theory. The alpha particle has insufficient energy to escape the nucleus, but it can "tunnel" through the potential energy barrier created by the strong nuclear force to achieve stability.
- **Electronics:** Quantum tunneling affects very-large-scale integration (VLSI) electronics via leakage currents and power loss, and it is fundamental in flash memory and devices like tunnel diodes, tunnel field-effect transistors, and quantum-dot cellular automata.
- **Josephson junctions:** These devices consist of two superconductors separated by a thin insulating layer. Superconducting pairs of electrons (Cooper pairs) can quantum tunnel through this barrier. The resulting "supercurrent" flows without any voltage, a phenomenon that has applications in:
 - **Superconducting Quantum Interference Devices (SQUIDs)** for measuring extremely small magnetic fields.

- **Quantum computing** to create and manipulate quantum bits (qubits).
- **Quantum Biology:** Electron and proton tunneling play essential roles in biochemical processes such as cellular respiration, photosynthesis, enzymatic catalysis, and DNA mutation mechanisms.
- **Biochemical reactions:** Quantum tunneling is a central, non-trivial quantum effect in quantum biology.
 - **Enzyme catalysis:** In many biochemical reactions, electrons and even protons rely on tunneling to move between molecules, which is a key part of enzymatic catalysis, photosynthesis, and cellular respiration.
 - **DNA mutations:** Proton tunneling can cause a base pair in the DNA double helix to spontaneously mutate by rearranging its hydrogen bonds. This is a possible mechanism for spontaneous DNA mutation.
- **Astrochemistry:** In the extremely low-energy environments of interstellar clouds, many chemical reactions (such as the formation of molecular hydrogen) would be energetically forbidden by classical mechanics. Quantum tunneling allows these reactions to occur. .
- **Energy Storage:** Quantum tunneling enables the creation of advanced ultra-capacitors and supercapacitors with high energy and power density, improving the performance of lithium-ion batteries and fuel cells by creating nanoscale electrodes with increased surface area.
- **Optics and Photonics:** Quantum tunneling aids in the development of ultra-fast optical switches and nano-scale optical devices, such as photonic crystals and optical resonators, which have applications in high-speed data transmission and nanoscale optics.

- **Flash Memory:** Exploits tunneling to change the charge state of floating gates in transistors, storing data non-volatily in devices like USB drives and solid-state drives.

Overall, quantum tunneling enables breakthroughs at atomic and nanoscale technologies, influencing microscopy, energy, electronics, biology, and photonics.

Quantum Tunnelling and the Light Speed Threshold

- Quantum tunnelling and the **light speed threshold** (the universal speed limit of relativity) seem to be pulling in opposite directions at first glance. Relativity says: *no particle carrying information or mass can travel faster than the speed of light in vacuum.*
- Quantum tunnelling, on the other hand, sometimes appears to let a particle “get through” a barrier faster than if it had gone over or around it—almost as if it were cheating the speed limit
- When a particle tunnels through a barrier, its wave function (the mathematical object that describes its probability of being somewhere) extends into the barrier. If the barrier is thin enough, there’s a finite chance that the particle will show up on the other side.
- Now, the time it takes for this tunnelling to occur is strange. In some experiments, it looks like particles “emerge” on the other side almost instantly, faster than light could have crossed the same distance.
- But this doesn’t mean the particle literally *travels through* the barrier at superluminal speed. Instead, tunnelling is a non-classical process where the concept of a well-defined trajectory inside the barrier simply doesn’t apply.
- In fact, most physicists say: the particle doesn’t really “cross” the barrier in the ordinary sense—it’s more accurate to say that the probability of finding it on the other side suddenly becomes nonzero.

- Crucially, **no usable information or signal** can be transmitted faster than light via tunnelling. This is why relativity is not violated. The appearance of faster-than-light behaviour comes from how we interpret timing in quantum processes, not from actual superluminal motion
- Quantum tunnelling seems to “shortcut” classical paths, giving the illusion of faster-than-light travel.
- But it does not transmit information or particles in a way that breaks Einstein’s light-speed barrier.
- It shows us that the quantum world doesn’t follow the same rules of locality and trajectories that we expect in everyday life

National Quantum Mission (NQM)

The National Quantum Mission (NQM) is a major initiative launched by the Government of India in April 2023 with a budget of about Rs. 6003.65 crore, spanning from 2023-24 to 2030-31. Its goal is to develop and scale up scientific and industrial research in quantum technology and create a vibrant ecosystem that makes India a global leader in this cutting-edge field.

Key objectives include:

- Developing intermediate-scale quantum computers with 50-1000 physical qubits within 8 years using platforms like superconducting and photonic technologies.
- Establishing satellite-based secure quantum communications within India over 2000 km and enabling long-distance quantum communication with other countries.
- Creating quantum networks, quantum sensing devices like atomic clocks and magnetometers, and quantum materials such as superconductors and novel semiconductors.

- Supporting research hubs focused on quantum computing, quantum communication, quantum sensing and metrology, and quantum materials and devices.
- Promoting technology development, entrepreneurship, skill development, industry partnerships, and international collaborations across 17 states and 2 union territories.
- Encouraging participation of women scientists nationwide.
- The mission aims to accelerate quantum technology-led economic growth and impact sectors such as healthcare, defense, finance, telecommunications, climate change, clean energy, and national security. It aligns with India's broader goals of Digital India, Make in India, Skill India, Start-up India, and the Sustainable Development Goals.
- The implementation architecture comprises four thematic hubs ("T-Hubs") functioning on a hub-spoke-spike model to foster research clusters and resource sharing. The focus areas of the mission span quantum computing, communication, sensing, and advanced quantum materials to support device fabrication.

Overall, the National Quantum Mission is a strategic effort placing India among the few leading nations worldwide investing in quantum science and technology to drive innovation, scientific excellence, and technological leadership in the quantum era

Key Directions for the Future of Quantum Tunnelling

1. Macroscopic Quantum Tunnelling

The Nobel Prize in Physics 2025 was awarded for demonstrating quantum tunnelling in macroscopic systems, such as superconducting circuits, which act as large-scale quantum objects. This milestone indicates that quantum tunnelling is not limited to microscopic particles, opening the door to engineering large quantum devices.

2. Quantum Computing and Quantum Sensors

The controlled use of quantum tunnelling in superconducting qubits is already laying the foundation for practical quantum computers and highly sensitive quantum sensors. Researchers aim to improve coherence times, error rates, and scalability of such systems for real-world deployment.

3. Fundamental Physics and Technology

New experimental techniques that probe tunnelling speeds and mechanisms challenge existing interpretations of quantum physics, such as Bohmian mechanics, and help refine our understanding of the tunnelling process. These insights are critical for developing models that optimize tunnelling-based devices.

4. Material Science and Nanoelectronics

As transistors scale below certain dimensions, tunnelling effects become unavoidable in microelectronics. Future research aims to control tunnelling in nanoelectronic components, pushing the limits of device miniaturization and energy efficiency.

5. Biological and Chemical Processes

Quantum tunnelling also plays a role in biological phenomena, such as enzyme reactions and prebiotic chemistry, indicating that future research could expand into biotech applications. Understanding the quantum nature of these processes may lead to breakthroughs in medicine and origin-of-life studies.

Emerging Technologies and Research

- Quantum tunnelling in superconducting circuits as a basis for quantum computers.
- Macroscopic quantum tunnelling experiments continue to refine our understanding, which will inform device engineering.

- Probing tunnelling times and dynamics with more sophisticated experiments aims to resolve long-standing debates on tunnelling speed and interpretation.
- Biological and chemical implications are being explored, with potential breakthroughs in understanding the quantum basis of life processes.

Concluding Outlook

The way forward involves leveraging these experimental advancements to develop robust quantum devices, deepen our theoretical understanding, and explore broader applications. The boundary between microscopic and macroscopic quantum phenomena is gradually shrinking, promising revolutionary innovations in computation, sensing, materials, and biology in the coming decades.