

1. 2025 Nobel Prize in Physics

John Clarke, Michel Devoret and John Martinis will share the 2025 Nobel Prize in physics for their discovery of a phenomenon called quantum mechanical tunneling in an electrical circuit.

Quantum Tunneling and Superconducting Circuits

Introduction – Quantum Tunneling Beyond Particles

Quantum tunneling is one of the most fascinating and non-intuitive phenomena in quantum mechanics. It refers to the ability of particles to penetrate and pass-through potential barriers that would be impenetrable according to classical physics. Traditionally observed in subatomic particles (like electrons or protons), recent experiments have shown that tunneling can also occur in engineered macroscopic systems such as superconducting electrical circuits. Scientists demonstrated that by organizing and controlling a large number of particles coherently, one can make them collectively exhibit quantum tunneling-like behavior even at a visible or measurable scale.

Historical Context and Quantum Foundations

Origin of Quantum Mechanics – Werner Heisenberg formally introduced quantum mechanics in 1925, revolutionizing the understanding of matter and energy at atomic and subatomic scales. Quantum mechanics replaced deterministic classical laws with probabilistic interpretations, explaining how particles can behave like both waves and discrete entities.

2025 – A Centenary Celebration – To commemorate 100 years of quantum mechanics, the United Nations has declared 2025 as the International Year of Quantum Science and Technology. This global observance aims to –

1. Celebrate the scientific breakthroughs since 1925.
2. Promote awareness of quantum research and innovation.
3. Encourage global cooperation in developing quantum-based technologies.

Quantum Technology – The Next Revolution – Quantum technology harnesses the unique principles of quantum mechanics – superposition, entanglement, and tunneling – to create devices with unprecedented performance. These technologies have potential applications in computing, communication, sensing, cryptography, and precision measurement.

Understanding the Josephson Junction

Josephson Junction – A Josephson junction is a key device in quantum electronics made of –

1. Two superconductors,
2. Separated by a very thin insulating layer (only a few nanometers thick).

Despite the insulating barrier, Cooper pairs (pairs of electrons bound together at low temperatures) can tunnel through this barrier without resistance – a phenomenon known as the Josephson effect.

The Josephson Effect – Proposed by Brian D. Josephson in 1962, this effect demonstrated that quantum tunneling can occur between macroscopic quantum states. When a supercurrent (a current with zero electrical resistance) flows through the junction –

1. Below a critical current, no voltage appears – the Cooper pairs remain trapped.
2. Due to quantum tunneling, some electron pairs “escape” across the barrier, generating a measurable voltage oscillation.

This is direct evidence that quantum mechanics governs even collective systems of millions of particles under suitable conditions.

Applications and Modern Relevance

1. Quantum Computing – Josephson junctions form the foundation of superconducting qubits, the building blocks of several quantum computers (e.g., IBM, Google, and Rigetti systems). They allow the creation of quantized energy states that represent quantum bits ($|0\rangle$ and $|1\rangle$) in superposition. In the field of Circuit Quantum Electrodynamics (cQED) – Superconducting qubits are coupled with microwave resonators, enabling precise control and measurement of quantum states.

2. Precision Measurements

Josephson Voltage Standards – Provide a quantum-based definition of the volt, ensuring extreme accuracy in electrical measurements.

SQUIDS (Superconducting Quantum Interference Devices) – Combine two or more Josephson junctions to detect ultra-weak magnetic fields, such as those from the human brain or Earth's crustal movements.

3. Quantum Technologies

Quantum Amplifiers – Enhance weak quantum signals while maintaining minimal added noise – essential for quantum communication.

Microwave-to-Optical Converters – Enable interface between quantum processors (operating with microwaves) and optical communication networks (operating with photons).

Quantum Simulators – Recreate complex quantum materials and chemical reactions in a controllable setup to study phenomena that are otherwise computationally intractable.

Broader Implications

From Quantum Foundations to Real-World Systems – The Josephson effect bridges quantum mechanics and macroscopic physics, proving that quantum rules can apply to engineered systems visible to the naked eye. This understanding has not only advanced fundamental physics but also laid the foundation for quantum engineering, a new discipline merging physics, materials science, and electronics.

Towards a Quantum Future – Continued innovations in superconducting circuits, quantum measurement, and quantum coherence are leading toward –

1. More stable quantum processors,
2. Ultra-sensitive sensors, and
3. Energy-efficient electronic systems.

The ongoing global push in quantum research (2025 and beyond) marks the transition from theory to technological transformation.

Source – <https://www.thehindu.com/sci-tech/science/2025-nobel-prize-in-physics-goes-to-trio-for-discovery-of-macroscopic-quantum-mechanical-tunnelling/article70133992.ece>

