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QUANTUM COMPUTERS AND THE 2025 NOBEL PRIZE IN PHYSICS

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ABSTRACT

In the 1980s, groundbreaking experiments with superconducting circuits, particularly Superconducting Quantum Interference Devices (SQUIDs), demonstrated that quantum effects extend beyond the atomic scale to macroscopic systems. These studies initiated the field of macroscopic quantum mechanics. Researchers such as Anthony Leggett and John Clarke observed phenomena such as quantum tunneling and superposition in Josephson junctions, illustrating that quantum mechanics applies to larger systems provided they are isolated from environmental disturbances. These discoveries led to the development of superconducting qubits for modern quantum computers and advanced the understanding of quantum decoherence, which explains how quantum systems lose their properties due to environmental factors. This work bridged the gap between the quantum and classical worlds, forming the foundation of contemporary quantum science and technology.

KEYWORDS: quantum computers, Josephson junctions, superconductors, macroscopic quantum mechanics, quantum decoherence, SQUIDs, quantum tunneling, Nobel Prize 2025.

1 INTRODUCTION

The Royal Swedish Academy of Sciences has awarded the 2025 Nobel Prize in Physics to John Clarke, Michel H. Devoret, and John M. Martinis, who demonstrated both the quantum tunnelling effect and quantised energy levels in a system small enough to fit in the palm of your hand. These advances have served to develop the next generation of quantum technology, including quantum cryptography, quantum computers and quantum sensors. According to ROGERS (1), John Matthew Martinis was born in 1958 and raised in San Pedro, California. He is of Croatian descent. His father was a Croat from Komiža on the island of Vis near Split, Croatia. His father immigrated to the United States from Yugoslavia, escaping the communist regime. His mother was born in San Pedro to parents who had also emigrated from Croatia. Martinis played a central role in the experimental demonstration of macroscopic quantum phenomena, including macroscopic quantum tunneling (MQT) and energy quantization. Martinis earned both his bachelor's degree (1980) and his Ph.D. (1987) in physics from the University of California, Berkeley. During his doctoral studies, he conducted research in John Clarke's laboratory, where he also collaborated closely with Michel Devoret. Motivated by theoretical predictions suggesting that quantum mechanical effects could manifest in macroscopic systems, the researchers sought to experimentally demonstrate that phenomena traditionally confined to the atomic and subatomic realms could emerge in large-scale electrical circuits. To accomplish this, they designed and fabricated a precisely engineered superconducting circuit, cooled to temperatures near absolute zero. The system incorporated a Josephson junction, consisting of a thin insulating layer placed between two superconductors. After graduating from the University of California, Berkeley, Martinis received a Bachelor of Science in physics in 1980 and a Doctor of Philosophy in physics in 1987. During his doctoral studies, he investigated the quantum behavior of a macroscopic variable, the phase difference across a Josephson tunnel junction. His doctorate advisor was John Clarke. During this time, he collaborated with Michel Devoret, a postdoctoral researcher at the time. In 1985, Clarke, Devoret, and Martinis presented their analysis of microwave pulses that demonstrated the quantized energy levels of a Josephson junction. This work would later become the basis for superconducting quantum computing.

ROGERS [(1)] mentions that' Michel H. Devoret born 1953, in Paris, is a French physicist recognized for his pioneering work in circuit quantum electrodynamics (circuit QED), a field that uses superconducting circuits to create and control qubits—the fundamental building blocks of quantum computers. His research has been central to demonstrating that quantum mechanical effects, traditionally associated with microscopic particles, can also occur in macroscopic systems. For these groundbreaking contributions, he was awarded the 2025 Nobel Prize in Physics, alongside John Clarke and John M. Martinis. Devoret completed his engineering degree in 1975 in Paris, followed by studies in quantum optics and a Ph.D. in physics from the University of Orsay in 1982. After moving to the United States, he joined John Clarke's laboratory at the University of California, Berkeley, where he collaborated with Clarke and Martinis on experiments exploring the limits of quantum mechanics. At

Berkeley, the team designed a superconducting circuit containing a Josephson junction and operated it at extremely low temperatures. Their experiment demonstrated macroscopic quantum tunneling: a large group of electrons collectively transitioned between energy states in a way predicted by quantum theory. The measurable voltage produced during this transition provided clear experimental evidence that quantum effects can manifest at a scale much larger than individual atoms, challenging classical assumptions and advancing the development of quantum technologies.

According to ROGERS [1] John Clarke (born February 10, 1942, in Cambridge, England) is an English physicist renowned for his pioneering research on superconductivity and Josephson junctions. These junctions allow pairs of electrons to tunnel between two superconductors through a thin insulating barrier, a purely quantum phenomenon. Clarke's work led to major advances in superconducting quantum interference devices (SQUIDs), instruments capable of detecting extremely small magnetic fields with remarkable precision. SQUID technology became an essential tool in both fundamental physics research and practical applications. After completing his bachelor's, master's, and doctoral degrees at the University of Cambridge, Clarke joined the University of California, Berkeley, in 1969, where he served as a professor of physics and senior scientist at Lawrence Berkeley National Laboratory. In the 1980s, he worked closely with Michel H. Devoret and John M. Martinis, forming a collaboration that would profoundly influence experimental quantum physics. At a time when quantum effects were believed to be restricted to microscopic systems, Clarke and his collaborators demonstrated that quantum phenomena could occur in macroscopic electrical circuits. Using carefully engineered superconducting circuits maintained at cryogenic temperatures, they observed macroscopic quantum tunneling (MQT) and energy quantization in large-scale systems. Their findings provided strong evidence that quantum mechanics governs not only atoms and particles but also larger, human-made devices. For these groundbreaking contributions, Clarke shared the 2025 Nobel Prize in Physics with Devoret and Martinis.

Unlike classical computers, which use bits as basic units of information (binary values of 0 or 1), quantum computers work with qubits (quantum bits). A qubit can represent 0, 1, or both simultaneously, thanks to the phenomenon of superposition. Furthermore, two qubits can be entangled, meaning that the state of one immediately influences the state of the other, regardless of the distance between them. These two phenomena — superposition and entanglement — are primarily responsible for the computational power of quantum computers. They allow a quantum machine to explore multiple solutions in parallel, instead of testing each one sequentially, as occurs in traditional computers.

Quantum mechanics has redefined physics since its inception in the early 20th century. Initially applied to microscopic entities such as atoms, molecules and photons, the extension of quantum principles—superposition, tunneling, and entanglement—into macroscopic systems remained a challenge for decades. Experiments in the 1980s, led by pioneering researchers such as John Clarke and Michel Devoret, bridged this gap by proving that quantum mechanical phenomena govern observable systems on human scales. These insights validated the universal scope of quantum mechanics and led directly to innovations, such as superconducting qubits used in modern quantum computers.

While these breakthroughs have primarily been experimental, their implications extend across multiple disciplines—linking physics to engineering, computer science, and even philosophy. This article revisits these transformative discoveries, emphasizing how their recognition in 2025 stands as a landmark in physics while also raising ethical, technological, and geopolitical questions about the role of quantum technologies in shaping humanity's future.

2 Superconducting Circuits and Josephson Junctions

According CALDEIRA and LEGGETT [(2)] the Josephson junction, a device composed of two superconductors separated by an insulating layer, plays a pivotal role in enabling macroscopic quantum phenomena. Its behavior, governed by the tunneling of electron pairs (Cooper pairs), reflects foundational principles of quantum mechanics. When arranged in superconducting circuits, Josephson junctions exhibit:

- **Phase coherence:** The current across a junction depends on the phase difference of superconducting wavefunctions.
- **Magnetic flux quantization:** Superconducting loops create quantized magnetic fields, evident in devices such as Superconducting Quantum Interference Devices (SQUIDs).
- **Energy dissipation patterns:** As fundamental building blocks, Josephson junctions help maintain coherence critical to quantum computing applications.

Mathematical principles underlying Josephson junctions:

Current-phase relation:

$$I = I_c sin\varphi,$$

where *Ic* denotes the critical current (the maximum current that can flow without resistance), and φ represents the phase difference between the superconducting wavefunctions across the barrier.

AC Josephson effect (voltage-phase relationship):

$$V(t) = \frac{\hbar}{2e}\frac{d\varphi}{dt},$$

where $\hbar$ represents the reduced Planck constant, and e symbolizes the elementary charge.

Such effects laid the groundwork for superconducting qubits, which exploit superposition and quantum tunneling to perform calculations far beyond classical capabilities. Furthermore, SQUIDs, as highly sensitive detectors of magnetic flux, supported experimental validations of quantum superposition in systems observable to the naked eye (CLARKE and BRAGINSKI [(3)]).

3 Quantum Decoherence and Environmental Coupling

(DEVORET [(4)]), mentions that one of the biggest obstacles in quantum computing is keeping qubits in a coherent state long enough to perform useful calculations. Quantum coherence refers to a system's ability to maintain its quantum state without external interference. Unfortunately, qubits are extremely sensitive to environmental noise, such as temperature, vibration, and electromagnetic radiation. Any disturbance can cause decoherence, destroying the quantum state and invalidating the calculation.

The lifetime of a coherent qubit is called its coherence time, and quantum computers need to perform all their calculations within this tiny interval—usually measured in microseconds or milliseconds.

The phenomenon of quantum decoherence, where quantum systems lose coherence due to environmental interactions, is a major limiting factor in scalable quantum computing. The *Caldeira-Leggett*[(2)] *model* formulates this interaction through the Hamiltonian:

$$H = H_s + H_B + H_{SB},$$

where H_S represents the system's Hamiltonian, H_B denotes the environment Hamiltonian, and H_{SB} symbolizes the interaction between system and environment.

This framework explains why macroscopic systems—despite being quantum in nature—exhibit classical properties. The time scale of decoherence (T_2) directly impacts the durability of quantum states, prompting the need for cryogenic shielding, error correction algorithms, and quantum orchestration in practical qubits (LEGGETT [(5)]).

4 Applications in Science and Technology

4.1 Quantum Computing and Cryptography

According MARTINIS [(6)], modern superconducting qubits represent the culmination of decades of quantum experiments. Their ability to perform calculations in superposed states enables new frontiers in:

- Breaking classical encryption algorithms (e.g., RSA).
- Creating quantum-secure communication protocols, such as quantum key distribution.

4.2 Artificial Intelligence and Optimization

Quantum devices improve machine learning efficiency. For instance, Google's quantum processor achieved a computational task (sampling random circuits) in seconds, unattainable within thousands of years on the fastest supercomputers.

4.3 Environmental Applications

Quantum computing can model chaotic systems—such as global climate models—with unprecedented accuracy, informing policymaking on renewable energy transitions and disaster prevention.

4.4 Discovery of New Materials

The discovery of new materials can be achieved through complex chemical simulations, where atomic structures can be rearranged.

4.5 Finance

In finance, quantum computing can optimize investments by analyzing the risks involved.

4.6 Health

Breast cancer may also suffer a major setback with quantum computing. It proved very effective in the early detection of signs of the tumor, which is fundamental to increasing the chances of curing patients.

5 Geopolitical and Ethical Considerations

5.1 The Quantum Arms Race

MOSCIONI [(7)] , said quantum computing has sparked competition between nations for quantum dominance. Governments are heavily investing in "quantum sovereignty" to harness its potential for national security and global influence. The United States, China, and the European Union lead this effort, with significant resources allocated to cryptographic advancements.

5.2 Ethical Challenges

While offering opportunities for humanity, quantum technologies pose challenges:

- **Economic inequality:** The high costs of research concentrate power in a few economies or companies.
- **Disruption of cybersecurity:** Quantum systems threaten existing encryption infrastructure.

A global framework to govern technological ethics in the quantum age is urgently needed.

6 Final Considerations

According ALI [8], Quantum computing has significant implications for cybersecurity and cryptography. Quantum algorithms, such as Shor's algorithm, can break many of the encryption systems currently used to protect data.

This raises concerns about the security of sensitive information, such as banking data and medical records. As a result, there is a growing demand for post-quantum cryptography, which aims to create security systems that are resilient to quantum attacks.

Quantum physics is the theoretical basis of quantum computing. Its principles allow qubits to function in ways that classical bits cannot. Quantum mechanics provides the foundation for phenomena such as superposition and entanglement, which are exploited to perform calculations that cannot be done with traditional computers. A deep understanding of these principles is crucial for the development of new quantum technologies.

The Nobel Prize in Physics 2025 is a milestone not only for the recognition of John Clarke, Michel Devoret, and John Martinis but for the fields of quantum science as a whole. Their work illustrates that quantum coherence, initially thought to be restricted to atomic systems, can govern macroscopic phenomena.

Beyond this scientific legacy, their contributions underscore the balance between opportunity and responsibility in applying quantum mechanics. As we advance in achieving quantum supremacy, the ethical and geopolitical complexities accompanying such breakthroughs require collective action. Responsible innovation, global collaboration, and scaling sustainability frameworks will define the legacy of quantum technology for decades to come.

The future of quantum computing is promising, but fraught with uncertainties and challenges. Researchers are constantly exploring new ways to improve the stability of qubits and develop scalable technologies. Cooperation between academia, industry, and government will be crucial to accelerating advances in this area. Furthermore, the emergence of new applications in sectors such as energy, healthcare, and finance could drive the adoption of this innovative technology, leading to a truly new paradigm in computing.

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