Nobel Prize in Physics 2025

Marcello Colozzo

Abstract

We discuss the Nobel Prize awarded to John Clarke, Michel H. Devoret, and John M. Martinis "*for the discovery of macroscopic quantum tunneling and of the quantization of energy in an electric circuit*".

Foreword

The prize recognizes the pioneering experiments of physicists Clarke, Devoret, and Martinis conducted in the mid-1980s at the University of California, Berkeley, which demonstrated for the first time conclusively that quantum phenomena are not confined to the microscopic world but can also occur in macroscopic systems, particularly superconducting circuits.

Mathematical modeling

A one-dimensional schematization of many problems involving three-dimensional physical systems is essential to reduce mathematical difficulties. Quantum mechanics (non-relativistic) is no exception to this rule of thumb. To recall the main notions regarding the classically mechanical behavior of a particle moving in a one-dimensional space containing a conservative force field, we consider the publication (in Italian) [1].

The subsequent transition to quantum mechanics triggers unprecedented effects, such as the tunnel effect. Let's see what it is.

Tunnel effect

The phenomenon of electrical conductivity and the atypical behavior of many electronic devices can be phenomenologically explained through the notion of a *potential barrier*. For example, we can consider an electron subjected to a force arising from a potential energy field $U(x)$ such as the one shown in Fig. 1.

Notation 1 *The potential energy $U(x)$ of the electron is related to the electric potential $V(x)$ by $U(x) = -eV(x)$ where $e > 0$ is the absolute value of the electric charge of the electron.*

According to classical mechanics the total mechanical energy of the electron is:

$$E = \frac{1}{2}mv^2 + U(x) \tag{1}$$

where m is the mass of the electron and v is its velocity. Now if $E < U_0$ from (1) we see that in order to pass through the "thickness" of height U_0 and width b, the electron would have to move with an imaginary velocity. The absurdity of this conclusion implies that for $E < U_0$ the electron does not have enough energy to penetrate the barrier (think of a tennis ball thrown against a wall). Quantum mechanics, however, tells a different story: by invoking wave-particle duality, we can imagine the electron crossing the potential barrier like a wave. In fact, the particle is described

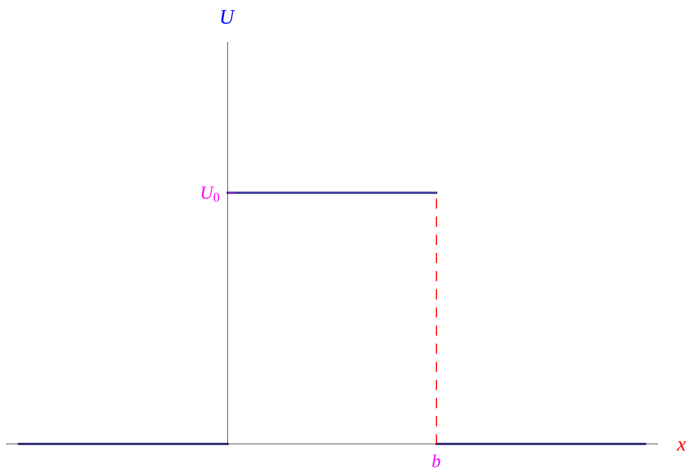

Figure 1: One-dimensional potential barrier.

by the propagation of a probability wave mathematically represented by a wave function $\psi(x,t)$. This is a mathematical object such that $|\psi(x,t)|^2 dx$ is the infinitesimal probability of finding the particle at the time t between x and $x+dx$. The standard mathematical procedure for determining $\psi(x,t)$ is to find the "stationary solutions" $u(x)$ of the appropriate wave equation (*Schrödinger equation*). Physically, each of these functions describes a quantum state with a definite energy (the so-called *energy eigenstates*). The $\psi(x,t)$ is then reconstructed through a suitable linear combination of solutions $u(x)$ for different values of the energy (the famous *quantum superpositions*). This is shocking because when the electron *rides* the wave $\psi(x,t)$ i.e. its quantum state is described by this function, it has *no* definite energy, and it is only through a measurement operation that we can know a definite value of the aforementioned quantity. In this case, $\psi(x,t)$ is said to collapse into the standing wave $u(x)$. Note that the fact of not having a defined value of energy is not a violation of the principle of conservation of energy (in fact we are studying a conservative system); simply put, it makes no sense to define energy in the quantum state $\psi(x,t)$. This counterintuitive behavior is actually a serious ontological problem of quantum mechanics.

The generic stationary solution $u(x)$, besides being mathematically easier to handle, provides a comprehensive picture of the electron's behavior. For example, in Fig 2 the stationary wave function $u(x)$ is plotted, which defines a value of the energy $E < U_0$.

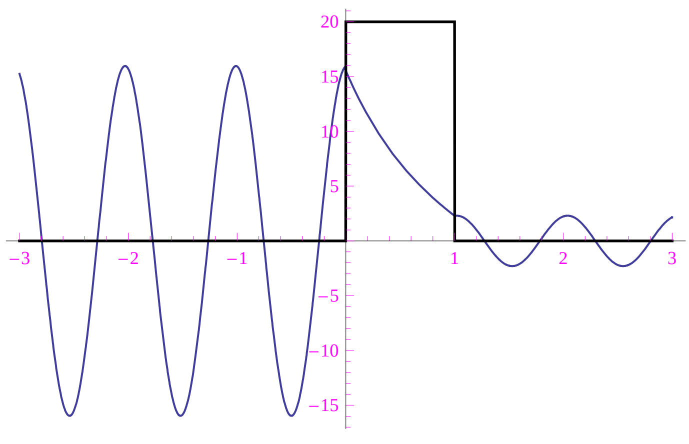

Figure 2: Tunneling effect simulated in the *Mathematica* computing environment. We used dimensionless variables to avoid rounding problems caused by the extremely small electron mass and Planck's constant.

Classically, the electron does not penetrate the barrier because it does not have enough energy. From a quantum mechanical perspective, however, we see from the aforementioned graph that there is a non-negligible probability of finding the electron *after* the barrier. This is the tunneling effect. We note, however, an exponential damping of the probability wave $u(x)$, which could be mistakenly interpreted as a dissipation of energy. But as stated, energy is conserved; on the other hand, the wave function is not associated with energy but with probability. This implies a reduction in probability, while taking into account that the total probability is conserved. In other words, the probability "lost" in the tunneling process is recovered by the reflected wave, which is not shown in Fig. 2. A detailed calculation of the reflection coefficient R of the barrier and the corresponding transmission coefficient T yields $R+T=1$, which expresses the conservation of probability in all and only quantum processes that do not involve the absorption or emission of particles.

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To phenomenologically interpret the behavior of a real conductor, namely the dissipation of the kinetic energy of conduction electrons into heat (the Joule effect), we must "add" something to our ideal model. We know that in an ideal lattice (in which the nuclei/ions are stationary at their respective nodes), electronic waves, although attenuated by tunneling processes, conserve the kinetic energy of the electrons. In the real case, however, the nuclei/ions oscillate around their equilibrium positions due to thermal energy. This deviation in the lattice periodicity can be interpreted in terms of particles as an inelastic electron-lattice collision, which dissipates the kinetic energy of the electron. In terms of wave mechanics, electronic waves interfere with lattice vibrations, the quantization of which yields the concept of a phonon. Ultimately, the dissipation of kinetic energy is the result of a complicated interaction between the electronic field and the phonon field (we are arguing in terms of quantum field theory, in which particles are excited states of a quantum field).

Environmental decoherence

In the previous section, we didn't say anything new: the tunneling effect, besides being as old as quantum mechanics, is the building block of our toy-model of the conductor/semiconductor/insulator [2]-[3], whose behavior is modulated by the height of a potential barrier periodic with the periodicity of the lattice. In electronics, we cannot help but recall the famous *tunnel diode*.

All these processes occur at the submicroscopic scale.

The burning question now is: is it possible to observe the tunneling effect at the macroscopic scale? To answer this question, let's refer to a generic conservative and non-relativistic quantum system S_q. The system is therefore described by a wave function ψ which in turn is expressed as a linear superposition of eigenstates of some observable (think of energy in the case of the electron in the previous section). As is well known, ψ is defined up to an inessential phase factor: what matters is the relative phase between the individual waves composing the wave function ψ. This is what is known as quantum coherence. However, in a realistic description, we must take into account the interaction of S_q with the "environment" A, which could be, for example, a measuring device for observables whose eigenstates we know (measurement of energy, position, momentum, angular momentum, etc.). The interaction is therefore an *entanglement* in the sense of quantum entanglement, which returns the composite system $S_q + A$ *nonseparabile*, to be nonseparable, and this destroys the correlation between the phases of the individual components of the wave ψ that describes the quantum state of S_q when it does not interact with A. The destruction of the correlation is followed by the cancellation of the superposition of the eigenstates, so that ψcollapses into an eigenstate that defines the value of the observable being measured. This is the *environmental decoherence* or *quantum decoherence*.

The decoherence framework thus explains the complicated process of measuring a quantum observable. Furthermore, it seems to satisfactorily interpret the transition from the submicroscopic to the macroscopic dimension (dominated by classical mechanics). Indeed, it is sufficient to replace the measuring apparatus A with the environment to which S_q belongs: the interaction with A is equivalent to a measurement process. Technically, S_q is said *to decoherence*. The dirty game is played by temperature, or rather, thermal energy: the interaction between S_q and the environment A is a thermodynamically irreversible process, and thermal energy is equivalent to a measurement process that determines the collapse of the wave function. It is therefore a well-defined physical process, characterized by a characteristic time τ_c which is the time interval necessary to cancel the quantum superpositions. This quantity is inversely proportional to the number of particles composing system A. For example, a cat is made up of approximately 10^{27} particles, which corresponds to a τ_c of the order of 10^{-23} s. This is why we do not see cats in superposition of life/death states (*Schrödinger's cat paradox*).

Macroscopic tunneling effect. Josephson junction

As established in the previous section, it seems that it is not possible to observe quantum behavior at the macroscopic scale. On the other hand, the well-known phenomenon of *Bose-Einstein condensation* highlights quantum mechanical behavior in a macroscopic system, provided that the latter is made up of $N \gg 1$ non-interacting particles (e.g., atoms) that obey Bose-Einstein statistics (and therefore have integer spin). By lowering the temperature below a critical value T_c (close to absolute zero), a macroscopic number of particles can be described by a single wave function, or *macro-wave function*. In other words, the system, despite being macroscopic, behaves like a gigantic atom. The entropy S of the system is zero since this quantity is proportional to the logarithm of the number of quantum mechanical states, and since we have only one state, $S = 0$. Bose-Einstein condensation has been observed in helium 4: the cancellation of entropy results in a cancellation of viscosity and therefore, of energy dissipation (*superfluidity* of helium 4).

Superconductivity is also due to Bose-Einstein condensation. However, it is not the system of conduction electrons that condenses, because electrons are fermions. What actually condenses is the system consisting of electron pairs in a spin singlet state, i.e., zero total spin, and therefore Bose particles. In the 1950s, it was realized that the formation of bound electron-electron states is favored by the electron-phonon interaction. Incidentally, good conductors such as copper and silver do not become superconductors, while poor conductors such as tin, mercury, and lead become superconducting for $T < T_c$. The formation of bound electron-electron states was studied by Cooper in 1956, which later gave rise to the BCE-theory (Barden, Cooper, Schrieffer).

Thus, in superconductors, the mechanism of electrical conductivity occurs through pairs of electrons – *Cooper pairs* – which establish a *supercurrent* that does not require an external electric field because there is no energy dissipation. Metaphorically, a Cooper pair behaves like a pair of football players passing the ball to avoid tackles from opposing players. In this metaphor, the ball represents the electric charge while the tackles represent collisions with the lattice. In the case of Cooper pairs, the electric charge transported is $2e$, where e is the absolute value of the electron's charge.

After this necessary premise, let's perform a conceptual experiment: we interface two metal conductors A and B with a thin oxide (insulating) layer C, and then apply a potential difference V across the junction. By measuring the current intensity I, we discover that the relationship between I and V is linear: the junction therefore exhibits ohmic behavior. Regardless of linearity, the flow of current is due to a microscopic tunneling process, because C behaves like a potential barrier that can still be crossed by electrons.

In 1962, physicist B.D. Josephson replaced conductors A and B in a pair A', B' of superconductors, creating the *Josephson junction*. The first effect observed was the presence of a supercurrent I in the corresponding electrical circuit, generated by a *macroscopic* tunneling process. In fact, what *tunnels* is not the single Cooper pair, but the entire condensate of pairs, which is a macroscopic system. Using evocative imagery, we dare say that microscopic tunneling is a bit like a bird that can escape from the cage through the bars. In the macroscopic (or Josephson) tunnel, however, an *entire flock* manages to escape through the bars.

Josephson won the Nobel Prize in Physics in 1973.

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In the 1980s and 1990s, laboratories such as those of John Clarke (Berkeley) and Michel Devoret (Saclay, then Yale) developed circuits with extremely pure and controlled Josephson junctions.

The goal was no longer simply to "see the tunneling" of Cooper pairs, but to directly measure the quantized levels of a macroscopic system: an entire circuit (essentially, a superconducting oscillator).

In other words:

- Josephson: macroscopic tunneling between superconductors.
- Devoret, Clarke, and Martinis demonstrate that an entire electrical circuit can behave like a quantum particle, with discrete energy states and observable and controllable quantum transitions.

This distinction is vital: the work of Devoret, Clarke, and Martinis is the experimental basis for superconducting qubits, the heart of the current quantum computing revolution.

Conclusion

Although macroscopic tunneling has been known since the 1960s, precision experimental implementations had to wait for the pioneering work of recent Nobel laureates. This work made it possible to: 1) isolate the system from noise so as to "see" individual quantum levels; 2) artificially manipulate the states; 3) lay the foundation for second-generation quantum technology.

Fundamental Scientific Publications of the Awardees

These papers are considered the seminal works that laid the foundation for the Nobel Prize:

On macroscopic quantum tunneling:

Devoret, M. H., Martinis, J. M., & Clarke, J. (1985). "Measurements of macroscopic quantum tunneling out of the zero-voltage state of a current-biased Josephson junction." Physical Review Letters, 55(18), 1908-1911.

In this seminal work, the team provided the first clear experimental evidence for quantum tunneling of a macroscopic variable (the phase of a Josephson junction) from a metastable energy state.

On the quantization of energy in a macroscopic circuit:

Martinis, J. M., Devoret, M. H., & Clarke, J. (1985). "Energy-level quantization in the zero-voltage state of a current-biased Josephson junction." Physical Review Letters, 55(15), 1543-1546.

This paper demonstrated, through microwave spectroscopy, the existence of discrete (quantized) energy levels in a macroscopic system, effectively treating the circuit as an "artificial atom."

A more detailed follow-up:

Martinis, J. M., Devoret, M. H., & Clarke, J. (1987). "Experimental tests for the quantum behavior of a macroscopic degree of freedom: The phase difference across a Josephson junction." Physical Review B, 35(10), 4682-4698.

This longer paper provides more details on the experiments and analysis that confirm the quantum behavior of their system.

Official Nobel Prize Documents

For a thorough understanding of the significance of the prize, the Royal Swedish Academy of Sciences provides excellent information:

Scientific Background to the Nobel Prize in Physics 2025: "for the discovery of macroscopic quantum mechanical tunneling and energy quantization in an electric circuit." The Royal Swedish Academy of Sciences, Stockholm.

This document, available on the official Nobel Prize website, offers a detailed scientific explanation of the laureates' work, its historical context, and its significance.

Popular Science Background to the Nobel Prize in Physics 2025: "Quantum properties on a human scale." The Royal Swedish Academy of Sciences, Stockholm.

A more accessible version for a non-specialist audience, which explains key concepts intuitively.

Textbooks and Monographs for Further Study

To place these topics in a broader context of physics, the following texts are recommended:

Quantum Mechanics and Macroscopic Phenomena:

Leggett, A. J. (2006). Quantum Liquids: Bose Condensation and Cooper Pairing in Condensed-Matter Systems. Oxford University Press.

Although focused on quantum liquids, the work of Anthony Leggett (2003 Nobel Prize in Physics) provided the fundamental theoretical foundation for understanding macroscopic quantum tunneling.

Caldeira, A. O. (2014). An Introduction to Macroscopic Quantum Phenomena and Quantum Dissipation. Cambridge University Press.

A text that directly addresses the topic of quantum phenomena at the macroscopic scale and the crucial role of dissipation and decoherence.

Superconductivity and Josephson Junctions (the key experimental system):

Tinkham, M. (2004). Introduction to Superconductivity (2nd ed.). Dover Publications.

A classic and fundamental text for understanding the physics of superconductivity and Josephson junctions, essential for the award-winning experiments.

Barone, A., & Paternò, G. (1982). Physics and Applications of the Josephson Effect. Wiley-VCH.

A comprehensive reference work on Josephson junctions, the electronic component at the heart of the three physicists' discoveries.

Review Articles

For an overview of the state of the art and development of the field:

Clarke, J., & Wilhelm, F. K. (2008). "Superconducting quantum bits." Nature, 453(7198), 1031-1042.

Written by one of the laureates, this article illustrates how the concepts they demonstrated led directly to the development of superconducting qubits, the fundamental building blocks of quantum computers.

Devoret, M. H., & Schoelkopf, R. J. (2013). "Superconducting Circuits for Quantum Information: An Outlook." Science, 339(6124), 1169-1174.

Another review article by one of the laureates outlining the trajectory from their seminal work to modern quantum technologies.

This bibliography provides a solid starting point for exploring both the original work that merited the 2025 Nobel Prize in Physics, as well as the theoretical context and subsequent technological applications that resulted.

References

[1] Colozzo M., Problemi unidimensionali.

[2] Colozzo M., A quantum physics toy model.

[3] Colozzo M., A quantum physics toy model (Part 2).

[4] Fisica statistica. Teoria dello stato condensato.