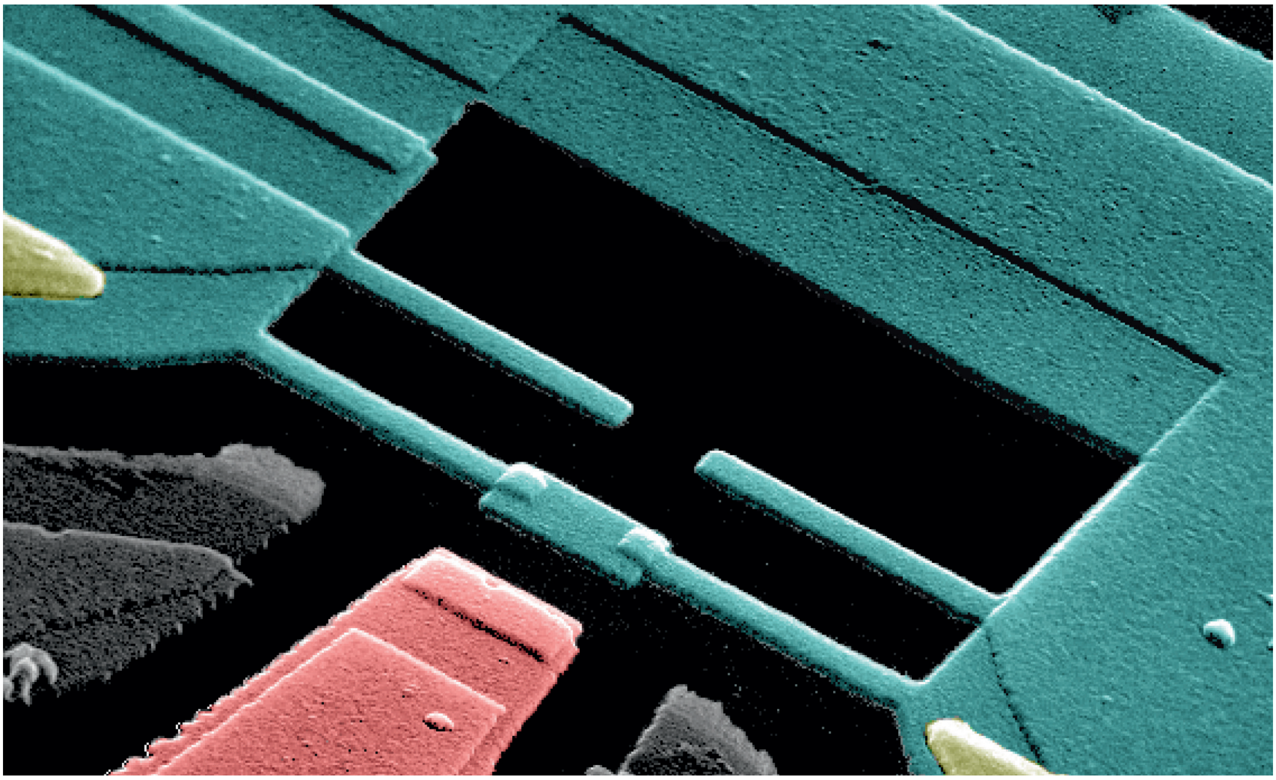
Quantronics

PHYSICS-NOBEL

The birth of quantum electronics

The Nobel prize for physics 2025 is shared by John Clarke, Michel H. Devoret, and John M. Martinis.

Hugues Pothier and Christoph Strunk

"Do macroscopic variables obey quantum mechanics?" The Nobel Prize for Physics is attributed this year to three physicists, John Clarke, Michel Devoret and John Martinis, who together carried out experiments that positively answered this question 40 years ago.

It is significant that this recognition arises on the International Year of Quantum Science and Technology, 100 years after the formulation of quantum mechanics. The work of this year Nobel prize laureates gave the initial impetus to a domain of research that not only spread to a large number of research laboratories, but also gave birth to private companies aiming at developing quantum circuits, some of them even aiming at a quantum computer.

The story began around 1980 with works of Anthony Leggett [1], who had proposed in 1978 to test the applicability of quantum mechanics to a macroscopic degree of freedom: the phase difference across a Josephson junction. A Josephson junction consists in two superconducting electrodes electrically coupled through a thin insulating layer by quantum tunneling (**Fig. 1a**). As in the normal state, i.e. above the superconducting transition temperature, where electrons tunnel independently, Cooper pairs that form below the transition temperature can tunnel through the barrier.

The condensate of Cooper pairs behaves collectively and is described as a whole with a macroscopic wave function with a phase φ. The number N of Cooper pairs in the condensate and the phase obey an uncertainty relation, analog to that between position and momentum. In an electrically isolated electrode, N does not fluctuate and φ fluctuates maximally. In presence of a strong Josephson coupling, the difference $N_1 - N_2$ in the number of Cooper pairs between the two electrodes fluctuates, while the phase difference $\varphi = \varphi_1 - \varphi_2$ is well determined. The two Josephson relations $I(\varphi) = I_c \sin\varphi$

◄ Quantronium-circuit (green) with a Cooper-Pair-Box in the center, a gate electrode to control the charge state (red) and quasiparticle traps (yellow) [7]

and $V = \hbar\dot{\varphi}/\, 2e$ describe the dynamics of φ, with I the electrical current and V the voltage, e the electron charge and $\hbar$ the reduced Planck constant. If one takes the time integral of IV using the Josephson relations, on obtains the energy $E(\varphi) = E_J\,(1 - \cos\varphi)$ stored in the Josephson junction when the phase changes from 0 to φ (**Fig. 1b**); the energy $E_J = \hbar I_c/2e$ is known as the Josephson energy. If one draws the analogy between $\boldsymbol{\varphi}$ and the position x of a (fictitious) particle, then $\dot{\varphi}$, which according to the second Josephson relation is proportional to the voltage, corresponds to the particle velocity. The dynamic of a junction is therefore that of a particle in a periodic potential (see **Table**).

The central question was then, whether the laws of quantum mechanics can (or should) be applied to this fictitious particle. Since the phase φ describes all the Cooper pairs in the electrodes, it is genuinely a macroscopic degree of freedom. In the absence of a current, the particle sits in a potential minimum. A bias current I_b through the junction corresponds to an external force that tilts the potential $E_{pot}(\varphi) = E(\varphi) - I_b\hbar\,\varphi\,/\,2e$. As soon as the tilt is such that the potential barrier disappears, the particle escapes and accelerates. Friction leads to a velocity limit, similar to what happens to a skydiver. For a Josephson junction, this translates to the appearance of a DC voltage as soon as the bias current exceeds the critical current: $I_b > I_c$.

In the experiment, the bias current is ramped up from zero. At finite temperature $T > 0$ the fictitious particle has thermal fluctuations and escapes already at $I_b < I_c$, with an "escape" rate $\Gamma(T)$. It switches from a superconducting state with $V = 0$ to a voltage state with $V > 0$. Because this is a statistical process, one has to repeat the current ramping several thousands of time. The probability of switching at a bias current I_b is represented with an histogram $P(I_b)$. In the classical regime, the temperature determines the width δI of the histogram. The corresponding activation energy is given by the depth of the potential well in which the fictitious particle is trapped.

If quantum mechanics applies, the particle in the well should display discrete energy levels (**Fig.1c**). In addition, at low temperature, one should observe quantum tunneling through the barrier, in addition to the thermal activation above the barrier. Leggett predicted that the tunneling of the phase would not be drastically suppressed by friction. The quantum escape rate Γ_Q is predicted to depend exponentially on the barrier height, as in the classical regime. To compare with the experiment, one can therefore express the escape rate in terms of an escape temperature T_{esc} that should correspond to the actual temperature in the classical regime, and to a constant in the quantum regime. One should therefore observe a saturation of T_{esc} below a temperature given by Γ_Q.

Correspondance between mechanical and electrical quantities

Particle in potential	x	$v = \dot{x}$	M	P	$-F_{ext}$	$E_{pot}(x)$	E_{kin}
Electrical analog in Josephson junction	φ	$V = \hbar\dot{\varphi}/2e$	$C(\hbar/2e)^2$	$Q = 2eN$	I_b	$E_{pot}(\varphi)$	$4E_CN^2$

Table. M and P are the mass and momentum of the fictitious particle; C is the capacitance between the superconducting electrodes; Q is the charge that passed from one electrode to the other; and I_b the bias current. $E_C = e^2/2C$ is the charging energy corresponding to a single electron charge on the capacitance.

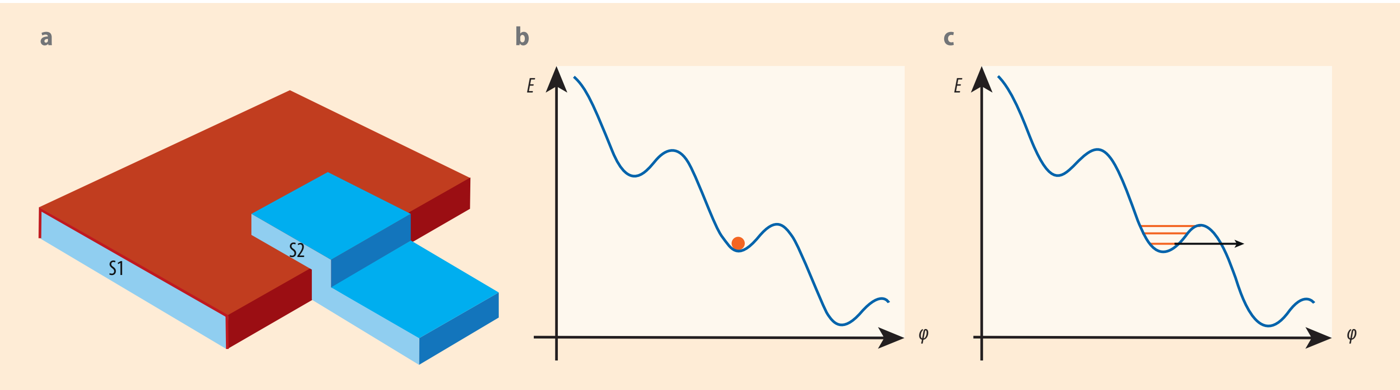

Fig. 1 A Josephson junction (a) consists in two superconducting films (S_1, S_2) coupled by an insulating layer (red) across which Cooper pairs can tunnel. In the classical regime, the phase can escape a potential well in der potential corresponding to a current bias junction Josephson junction (b) only by thermal activation. For a junction in the quantum regime, the phase is delocalized in the potential well (c) and forms discrete states (orange). In this case, the particle can also escape the potential well by macroscopic quantum tunneling through the barrier.

Fig. 2 John Clarke (a) started in 1982 the groundbreaking experiments with John Martinis (b, bottom left) , Michel Devoret (right), here during a hike at Mount Tamalpais near Berkeley in 1984. Also in the picture: Daniel Esteve and Cristián Urbina.

A crucial element in the proposal of Anthony Leggett is that the detailed analysis of the thermal activation regime gives access to all the parameters needed to precisely predict the quantum behavior, in particular the saturation temperature. The tunneling of the phase postulated by Leggett is very different in nature from the tunneling of Cooper pairs through the tunnel barrier: the barrier height $\Delta U(I_b)$ is determined only by the electrical currents I_b und I_c, and not by the tunnel barrier.

The prize laureates

Like Brian Josephson, after whom the Josephson junctions are named, John Clarke did his PhD at Cambridge under the supervision of Brian Pippard. In 1964, Clarke had developed a primitive version of a SQUID (Superconductive Quan-tum Interference device, a parallel combination of two Josephson junctions), which he had christened SLUG. Having closely worked with Pippard, Josephson and Michael Tinkham, he was one of the first experts of superconducting devices.

In 1982, Clarke decided to carry out with a French post-doc, Michel Devoret, and a PhD student, John Martinis, the experiment proposed by Leggett. Devoret had a background in telecommunication techniques, a passion for quantum physics, and dreamed of combining them. The quantum regime could only be reached at very low temperatures, which made the know-how of Devoret with dilution refrigerators instrumental. As John Martinis recalls, he had been starting to build such a fridge himself. When Devoret arrived in Berkeley in 1982 and saw it, he commented [2]: "I think the fastest way for us to do this experiment is to get a hacksaw and cut it in two[, and start over]". They put together this fridge with the help of two other fellows of Devoret who had also done their PhD at CEA-Saclay and joined Clarke's lab for a post doc: Cristián Urbina and Daniel Esteve.

The experiments

The experiments distinguished by the Nobel prize were carried out on a Nb/NbO$_x$/PbIn junction (**Fig. 3a**). The goal of the experiment was to measure how the escape temperature T_{esc} crosses over from the classical regime to the quantum saturation. In addition to the required low temperature, an additional difficulty was to get rid of a current thermal noise through the junction, which arised from resistances in the biasing scheme. Special microwave filters were developed to damp the resulting vibrations of the potential, which could give rise to a saturation of the switching histogram identical to the signature of quantum tunneling. A saturation of T_{esc} was observed in the quantum regime (full disks in **Fig. 3b**), but they could exclude this being due to an incomplete thermalization of the sample [3]: in a control experiment, lower escape temperatures than the saturation value were observed by reducing the critical current of the junction with a magnetic field, thereby reducing the crossover temperature (open disks in **Fig. 3b**).

In a further development of the experiment, the laureates demonstrated an even more specific signature of quantum mechanics: the existence of discrete energy levels in the potential well [4]. According to theory, the junction in the zero-voltage state should be described with discrete energy levels, similarly to a real particle trapped in a potential well. As in atomic physics, the states quantization can be evidenced through spectroscopy experiments, which can be done by shining microwaves on the Josephson junction. When the junction is excited to a higher energy level, it can more easily escape the zero voltage state, which is seen as peaks in the escape rate **(Fig. 3c).** This evidence of quantum behavior marked the beginning of what is now the booming field of superconducting quantum circuits, currently considered among the most promising candidates for the realization of a quantum computer.

In 1985, Michel Devoret, Cristián Urbina and Daniel Esteve had all returned to CEA-Saclay, and decided to pursue the field of research initiated in Berkeley: quantum electronics, hence the name of the group they founded: Quantronics. John Clarke spent a sabbatical semester in the Quantronics group in 1985-86, whereas John Martinis was the first post-doc after completing his PhD in 1987. In this period started a long-lasting collaboration with the theory group of Hermann Grabert in Essen, then Freiburg.

Subsequent developments

After a period dedicated to the experiments described above and their interpretation, John Clarke returned to his first love: SQUIDs, turning them into magnetometers, gradiometers, highly sensitive voltmeters, and quantum-limited amplifiers. The devices he developed found applications in various domains, like low magnetic field magnetic resonance imaging, detection of the magnetic signal of the brain to diagnose epilepsy, as well as detectors for geology or dark matter search [5]. In the perspective of applications, he worked also with high-temperature superconductors, and explored extensively the sources of noise.

The trajectories of Michel Devoret and John Martinis were remarkably interlaced during their whole carriers, sometimes crossing, in other matters following one another or evolving in parallel. To this day, they maintain a close and friendly relationship. At the end of the 1980s and throughout the 1990s, the focus of both Devoret and Martinis switched to charging effects: the newly developed lithography techniques allowed to make tunnel junctions so small that the "charging energy" E_C, the electrostatic energy corresponding to a single electron charge on the junction capacitance, was larger than temperature. In the Quantronics group, the experiments first dealt with non-superconducting circuits. The single-electron box, the electron turnstile (in collaboration with the group of Hans Mooij in Delft) and the single electron pump demonstrated the ability to control charges at the single electron level.

John Martinis, on his side, had taken a position at the NIST in Boulder, and was also working on single electron effects with a focus on instrumentation and metrological aspects, in particular on the accuracy of single electron pumps. He also explored the possibility to use Josephson junction for X-ray detection for material analysis and astronomy.

The combination of charging effects with superconductivity opened new perspectives: the Quantronics group demonstrated that the charge of a small superconducting island, the Cooper pair box, is quantized in units of $2e$. This means that parity plays a role in the superconducting state, even if the number of electrons involved is of the order of 10^9. Then, in 1998, superpositions of charge states differing by a single Cooper pair were evidenced in a Cooper pair box.

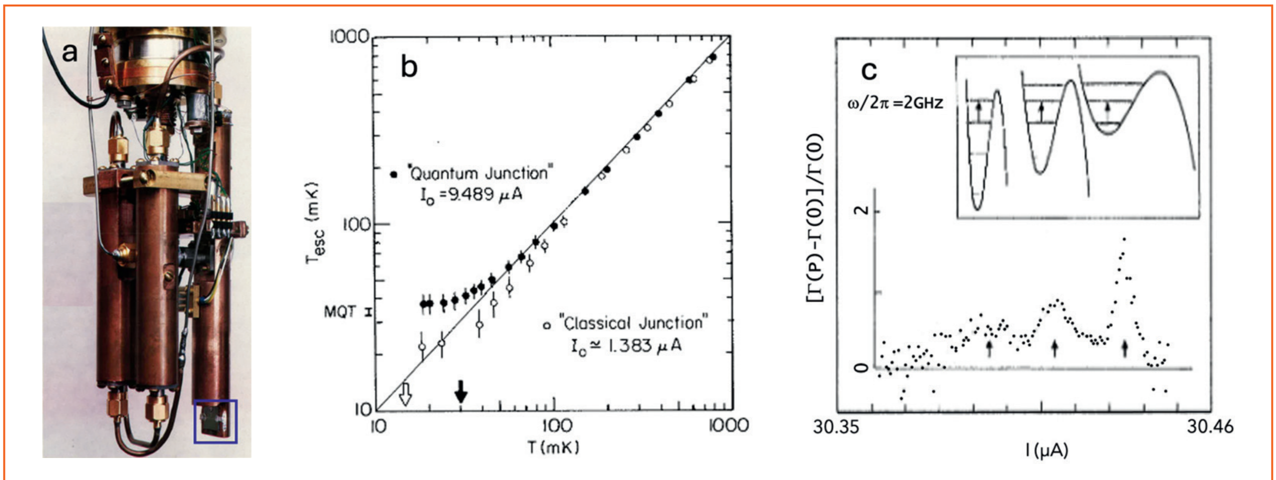

Fig. 3 The setup used for the experiment (a) shows the mixing chamber of a dilution refrigerator, which provides the cooling capacity, the Josephson junction (blue square), and the cylindrical copper powder filters, which shield the Josephson junction from microwave noise. The tunnel experiment (b) shows the escape rate expressed in terms of the corresponding escape temperature T_{esc} for a contact in the classical regime (open disks) and a contact in the quantum regime (full disks), for which T_{esc} saturates at a temperature significantly higher than the lowest temperature (18 mK) achieved in the classical regime. The saturation temperature (error bar labeled MQT on the left axis) and the cross-over temperatures (arrows on the bottom axis) calculated for macroscopic quantum tunneling are in good agreement with the experimental results [3]. In presence of a microwave excitation at $v = 2$ GHz, the dependence of the tunneling rate as a function of the bias current displays several peaks (arrrows) that correspond to transition between energy levels in the potential well. The inset shows the potential landscape for increasing bias currents [4]. When the current is increased, the potential becomes flatter, so that the frequency $v = 2$ GHz corresponds to different transition energies.

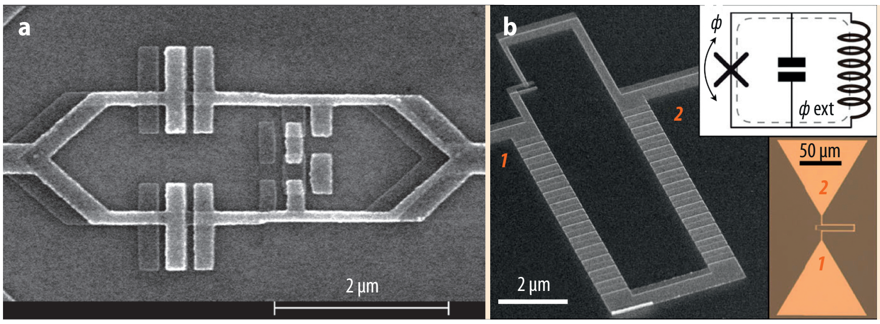

Fig. 4 (a) Flux qubits use basis states having currents flowing in opposite directions. The qubit loop is coupled to a SQUID loop for readout [9].

(b) The fluxonium is a variant of the flux qubit that possesses an extremely high coherence time [12].

A major breakthrough was accomplished by Yasunobu Nakamura in NEC, when he managed to demonstrate temporal Rabi oscillations with a Cooper pair box [6]. This marked the first successful experimental control of the time evolution of a man-made quantum circuit, representing an essential step forward on the path to quantum computers.

Noise and decoherence

In 2002, the Quantronics group invented the Quantronium [7], the first superconducting qubit that allowed the controlled steering of superposition states, with lifetime and coherence time much larger than the manipulation time (**Fig.** on the front page). The main limitation of charge qubits was the noise from charged impurities. The Quantronium could be used at a working point insensitive to it at first order, a concept that would later become popular under the name of "sweet spot". Shortly after, Martinis, together with Urbina who was on sabbatical at Boulder, developed another kind of superconducting qubit, the "phase qubit" [8], very much in the line of the initial Berkeley experiment. In Delft, the time control of flux qubits, which rely on persistent currents running in opposite directions, was achieved in 2003 [9] (**Fig. 4a**). In 2004, John Martinis took a professor position at University of California in Santa Barbara. His further research aimed in particular at understanding the material issues leading to decoherence.

In 2002, Michel Devoret was offered a position in Yale, where he started a close and fruitful collaboration with Rob Schoelkopf on the experimental side, Steve Girvin and Leonid Glazman on the theory side. The techniques of circuit quantum electrodynamics (circuit QED [10]) were invented in Yale, and Devoret participated to their development, and to the invention of a charge-insensitive version of the Cooper pair box: the Transmon. He also worked on amplifiers close to the quantum limit. He named one type of amplifier he invented in clear reference to Clarke's SLUG: the SNAIL (for Superconducting Nonlinear Asymmetric Inductive eLements).

From 2006 to 2012, Devoret taught regularly in Paris, where he had been appointed at a chair of Mesoscopic Physics at Collège de France. At this occasion, in 2008, he founded with Benjamin Huard the Quantum Electronics group at Ecole Normale Supérieure (Paris). In this period, Clarke worked on "flux Qubits" that could be coupled and measured using SQUIDs [11].

In 2009, Devoret enriched the family of superconducting qubits with a novel member: the Fluxonium [12], based on the parallel combination of a Josephson junction, a large inductor and a capacitance (**Fig. 4b**). It was designed to be particularly insensitive to charge noise and soon after showed record coherence time exceeding 1 ms. In the 2010s, several visits of Mazyar Mirrahimi at Yale lead to the invention and realization of "cat qubit" [13]. Here, the qubit states are encoded in superpositions of modes of the electromagnetic field in a microwave cavity, which can be realized thanks to the coupling to a Josephson junction. In analogy to Schrödinger's cat, two Glauber states with opposite phases are superposed, so that the field amplitude oscillates upwards and downwards simultaneously.

In addition to numerous works related to the theory of amplification, in close relation to the quantum amplifiers he designed, Devoret has also several contributions on the theory side. For example, the theory of the influence of the electromagnetic environment of a junction on the tunneling rate, developed through collaboration between Quantronics group and Hermann Grabert's team, established a solid understanding of the Coulomb blockade.

From research to industry

With the progress in the qubits properties and their couplings, large companies started to consider developing a quantum computer out of superconducting circuits. In 2014, John Martinis was hired by Google Quantum AI Lab, where he stayed till 2020. He lead the team that coupled tens of transmon qubits, and coined the name "quantum supremacy" for circuits that would outperform classical computers.

On his side, Michel Devoret became 2021 scientific advisor of the French company Alice and Bob, which aims is to develop a quantum computer with cat qubits, and left it when he was hired by Google in 2024. In addition to developing better qubits, Devoret and Martinis have been very involved in Quantum error correction, which is (much more than in classical computers) necessary to deal with the effects of bit errors. Martinis worked on the implementation of the "surface code" on Google chips, while Devoret considered the possibility of having autonomous error correction by mastering dissipation in cat qubits (dissipation engineering).

The realization of a quantum computer would answer the crucial question of whether a large system of qubits can be reliably entangled or whether this is impossible for a fundamental reason. In this way, the development of complex circuits with many qubits, which is actually driven by application interests, also raises new fundamental questions for quantum theory.

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