Scientific Background to the Nobel Prize in Physics 2025

"FOR THE DISCOVERY OF MACROSCOPIC QUANTUM MECHANICAL TUNNELLING AND ENERGY QUANTISATION IN AN ELECTRIC CIRCUIT"

The Nobel Committee for Physics

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The Royal Swedish Academy of Sciences has decided to award
the Nobel Prize in Physics 2025 jointly to

John Clarke, **Michel Devoret** and **John Martinis**

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

Quantum mechanical tunnelling

Soon after the publication of Erwin Schrödinger's equation in 1926 (awarded with a Nobel Prize in 1933), solutions were found where the wavefunction penetrates into classically forbidden regions, i.e. where the total energy of the particle was lower than its potential energy in the region. Although the wavefunction is exponentially decaying under the barrier, for finite length barriers, the wavefunction exists also on the other side of the barrier. Thus, there exists a finite probability for the particle to pass the barrier, although it does not have enough energy to do so classically.

An early successful application of this theory was the explanation of alpha decay, where the alpha particle is confined in the nucleus by a potential barrier but has a finite probability to tunnel through this barrier. Tunnelling also explained why radioactive decay is a probabilistic process, where the half-life crucially depends on height and thickness of the potential barrier. Tunnelling is also necessary for fusion to occur in our Sun, where the temperature and pressure are actually too low to classically allow two protons to overcome the Coulomb repulsion and form a helium nucleus.

Quantum tunnelling is important not only for radioactive decay: the 1973 Nobel Prize in Physics was awarded with one half to Leo Esaki and Ivar Giaever for their experimental discoveries regarding electron tunnelling phenomena in semiconductors and superconductors, respectively. Giaver's 1960 experiments confirmed the existence of an energy gap in superconductors, something predicted by John Bardeen, Leon N. Cooper and Robert Schrieffer in 1957. Their BCS theory was awarded with the Nobel Prize in Physics 1972. The other half of the 1973 Nobel

Prize in Physics was awarded to Brian Josephson, whose theoretical predictions are essential also for this year's Prize, as we will see below.

Cooper pairs, macroscopic population of quantum states and Josephson junctions

The BCS theory posits that electrons, being fermions, pair up into so-called Cooper pairs, which are composite bosons. To a very good approximation, the BCS ground state can be understood as a macroscopic Bose-Einstein condensate of these bosonic Cooper pairs. This state is described by a complex order parameter, which in many respects can be thought of as an effective wavefunction of the center of mass of the condensed Cooper pairs [1].

In 1962 Brian Josephson predicted that Cooper pairs can tunnel without resistance across an insulating barrier giving rise to a zero-voltage current across a tunnel barrier between two superconductors. This so-called Josephson effect was experimentally confirmed at Bell Labs as early as 1963, and in 1964, a very sensitive magnetometer called the Superconducting Quantum Interference Device (SQUID) was developed at Ford Research Labs [2].

Superfluidity is another phenomenon related to Bose-Einstein condensation of a macroscopic number of bosons into a single state. At low enough temperatures ^{4}He atoms, which are bosons, occupy a single macroscopic superfluid state. The interaction between the atoms in the liquid state makes the exact description non-trivial. ^{3}He atoms are fermions, but they can also form Cooper pairs and at low enough temperatures, condense into a superfluid phase. The experimental discovery of this phase was awarded the Nobel Prize in Physics in 1996, to David M. Lee, Douglas D. Osheroff and Robert C. Richardson. In contrast to the original BCS condensate, the ^{3}He condensate is anisotropic and its description is more complicated. In 2003, Anthony Leggett was awarded the Nobel Prize in Physics for his contributions to this theory.

Schrödinger cat states and macroscopic quantum tunnelling (MQT)

In all of the above examples a large number of independent particles occupy a single quantum state, leading to remarkable properties such as charge and mass currents that flow without dissipation. The most straightforward example of such a state is N particles in a product state

$$\Psi(x_1, x_2, \dots, x_N) = \Psi(x_1)\Psi(x_2) \dots \Psi(x_N).$$

Here, a measurement of any of the N particles would leave the state of the other N-1 particles unchanged. The wavefunction can also be a product of superpositions of two different states

$$\Psi(x_1, x_2, \ldots, x_N) \propto [\Psi_L(x_1) + \Psi_D(x_1)][\Psi_L(x_2) + \Psi_D(x_2)] \ldots [\Psi_L(x_N) + \Psi_D(x_N)].$$

Inspired by Schrödinger's cat discussed below, we denote them L (living) and D (dead). On this product state, a measurement distinguishing between L and D on any single particle would indeed collapse the superposition of the measured particle, but the rest of the condensate would be unaffected. This feature of a product state gives an intuitive picture of the robustness of macroscopic condensates.

Quantum physics, however, allows for other types of many-particle states. For example, the superposition of two product states, one with all N particles in the L state, and the other with all N particles in the D state,

$$\Psi(x_1, x_2, \ldots, x_N) \propto \Psi_L(x_1)\Psi_L(x_2) \ldots \Psi_L(x_N) + \Psi_D(x_1)\Psi_D(x_2) \ldots \Psi_D(x_N).$$

Here a measurement that distinguishes between the L and D state on any single particle will collapse the superposition for all particles. This macroscopic quantum state is much more sensitive to interactions with its environment.

Such states are sometimes called "cat states", named after Schrödinger's famous thought experiment. Upon decay, a radioactive substance triggers a hammer to break a bottle of poison. The microscopic superposition inherent in radioactive decay, e.g. due to tunnelling of an alpha particle, is thereby coherently connected to the superposition of a living and dead cat. Schrödinger's cat illustrated the absurdity of quantum physics at the macroscopic scale. In practice, the cat superposition would decay extremely fast due to interaction with the environment.

Towards MQT in superconducting circuits

What if a smaller version of the Schrödinger's cat thought experiment could actually be performed in superconducting or superfluid systems? This was one of the questions formulated by Leggett in 1978 [3]. He suggested that quantum tunnelling between the two macroscopically distinct components of such a cat state could be realized in superconducting circuits, at milli-Kelvin temperatures. One reason that such Macroscopic Quantum Tunneling (MQT) might be found in superconducting circuits is that their very low resistance indicates that they have very weak coupling to dissipative degrees of freedom in the environment. Together with his PhD student Amir Caldeira, Leggett investigated how the tunnelling rates would be affected by a weak remaining coupling to a dissipative environment [4].

The current-biased Josephson junction

Leggett initially considered a superconducting SQUID loop, but the same type of physics could be realized in an even simpler system: a current biased Josephson junction [5] (see Fig. 1).

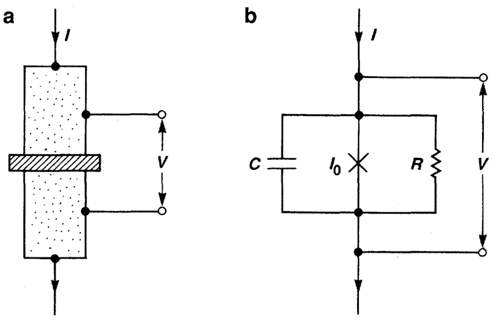

Figure 1*. a) A Josephson junction typically consists of two superconducting leads separated by an insulating tunnel barrier. A current I can pass through the junction and the voltage V across the junction can be measured. b) The junction is characterized by its critical current I_0 and capacitance C. The resistance R models all the dissipation in the system and is typically frequency dependent. In order to theoretically predict the MQT rate, the damping resistance must be characterized. (Figure from [6].)*

The two Josephson relations for the ideal junction read

$$I = I_0 \sin\delta \text{ and } \dot{\delta} = \frac{2e}{\hbar} V,$$

where the first (DC) equation relates the current I through the junction to the macroscopic phase difference δ. This phase difference of the order parameter across the junction is the same for all of the large number of Cooper pairs in the system. The second (AC) equation gives the time evolution of δ in terms of the voltage V across the junction. Including also the current that flows through the capacitance in the case of a time-dependent voltage, we arrive at

$$I = I_0 \sin\delta + \frac{\hbar}{2e} C\ddot{\delta}\,.$$

Neglecting dissipation, we can interpret this equation as Newton's equation for a fictitious particle with coordinate δ, having a mass proportional to the capacitance. The force acting on this particle is conservative, and integrating it with respect to the coordinate gives a potential $U(\delta) \propto -[\cos\delta + \left(\frac{I}{I_0}\right)\delta]$, also called a tilted washboard potential.

We can control the bias current I, and if it is set lower than the critical current ($I < I_0$), the potential has a series of metastable local minima, where the particle is trapped, resulting in a state with no voltage ($V \propto \dot{\delta} = 0$) across the junction (see Fig. 2a.). Raising the bias current above the critical current ($I > I_0$) forces the particle into a running state with non-zero voltage ($V \propto \dot{\delta} > 0$, see Fig. 2b). For $I < I_0$ and at zero temperature, a classical particle would be trapped forever at the bottom of the local minimum (see Fig. 2c), while a quantum mechanical particle would eventually tunnel out of the local minimum (see Fig. 2d).

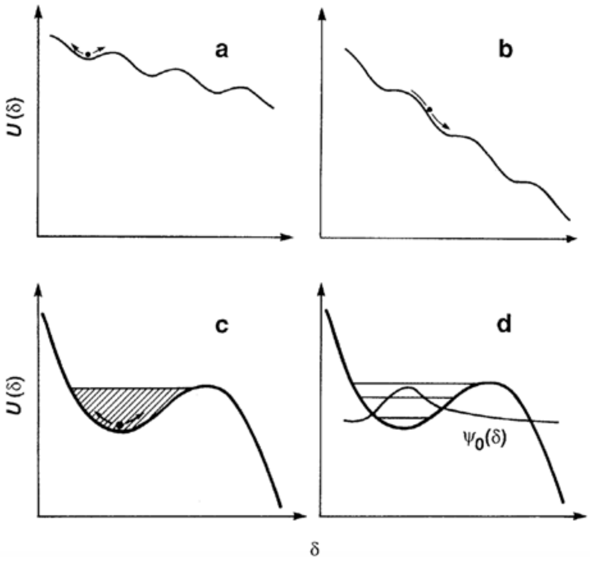

Figure 2. *The tilted washboard potential for a)* $I < I_0$*, where the particle can be trapped in a metastable local minimum, and b)* $I > I_0$*, where the particle accelerates and a finite voltage* $V > 0$ *appears. The experimental question is whether the macroscopic degree of freedom always obeys c) classical dynamics illustrated by a continuous energy range or d) quantized dynamics with discrete energy levels and macroscopic quantum tunnelling. (Figure from [6].)*

Experimental evidence for MQT

In the beginning of the 1980s, a number of groups looked for experimental evidence of macroscopic quantum effects in superconducting circuits. The experiments using the current biased Josephson junction [7-9] typically ramped up the current bias and registered the value at which a voltage was detected. Repeating this measurement, typically between 10^3 and 10^5 times for, a distribution of current values where the particle "escaped" could be generated at each temperature.

Lowering the temperature from the classical regime of thermally activated escape, the average escape current rapidly increases. Eventually a crossover temperature is reached, below which the distribution of escape currents becomes independent of temperature. In the low-temperature regime, the escape current distribution might be determined by macroscopic quantum tunnelling.

A problem was that a saturation of the escape current distribution at low temperature could also be explained by excess noise that is not in thermal equilibrium with the thermometer measuring temperature, for example microwave black-body radiation from some warmer part of the experimental setup. Physicists working in the field today are well acquainted with such excess noise and methods have been perfected to sufficiently reduce it. For a decisive proof of macroscopic quantum tunnelling, the excess noise must be eliminated and experimental results compared to theory, where the junction parameters and the environmental damping resistance are not fitting parameters but independently measured quantities [10].

The Berkeley group experiments – resonant activation, MQT and energy quantization

John Clarke joined the University of California at Berkeley (USA) in 1969, where he began working on superconducting junctions and their applications, e.g. very sensitive magnetometry and bolometry. Together with his senior PhD student John Martinis and post-doc Michel Devoret from the Centre d'Etudes Nucleaires de Saclay, France, they set up a series of experiments that would confirm the existence of MQT beyond reasonable doubt [11-13].

In their setup, they used a carefully designed filter chain, with over 200 dB damping over the frequency range 0.1 to 12 GHz, using newly developed copper powder microwave filters. The thermal anchoring of the filter chain at the different temperature stages of the cryostat is important, given that black body radiation from the filters themselves is emitted at the temperature of the filters.

Another very important part of the setup was a weakly coupled microwave control line for resonant activation of the junction [11]. Resonant activation allowed for *in situ* determination of the junction’s plasma frequency, i.e. the resonant frequency of the particle in the local minimum in the fully classical regime. The width of the activated resonance also allowed for characterization of the damping resistance. The junction’s critical current could be determined without microwave activation. Thus, all input parameters of the theory could be independently determined.

The researchers then measured escape rates below the crossover temperature in the expected regime of macroscopic quantum tunnelling. They could finally obtain quantitative agreement with theory (see Fig. 3).

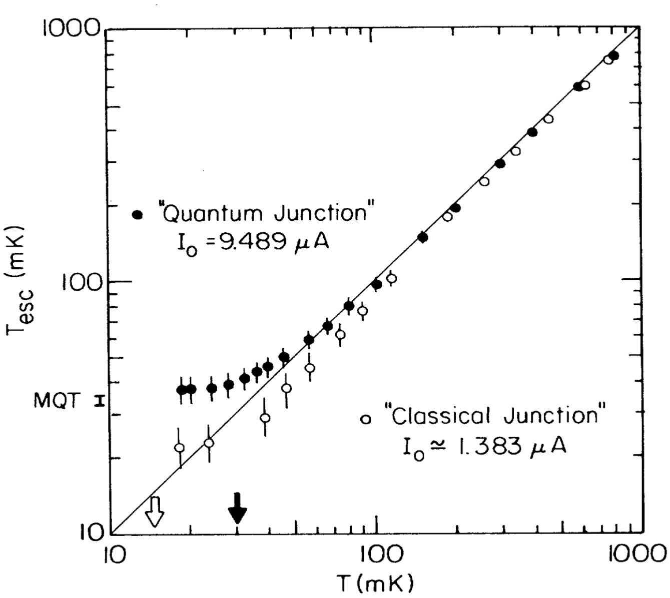

Figure 3. *The effective escape temperature, i.e. the temperature that would give the measured escape rate, as a function of real temperature together with error bars. For the "Classical Junction", the critical current has been suppressed by a magnetic field. The theoretical prediction for the MQT escape temperature is marked on the y-axis. The black arrow on the x-axis denotes the theoretical prediction for the crossover temperature for the quantum junction, and the white arrow, the classical junction. The measurement of the classical junction demonstrates that the sample is indeed cooled below the crossover temperature of the quantum junction. (From Fig. 2 in [13].)*

In addition to quantitative analysis of MQT, resonant activation allowed for microwave spectroscopy of the macroscopic state of the junction. According to the Wentzel–Kramers–Brillouin (WKB) approximation, the wavefunction of the excited states "sees" a thinner tunnel barrier and the escape rate from this excited state should be faster than from the lowest state of the well. The tunnelling from the first, second and third excited state of the well was experimentally observed and the excitation energies agreed with the single particle picture. The fictitious "particle" in this case is indeed a macroscopic degree of freedom describing the phase difference seen by all the Cooper pairs in the junction [12] (see Fig. 4). The experiment was a type of spectroscopic measurement that demonstrated quantized energy levels in a single macroscopic quantum system.

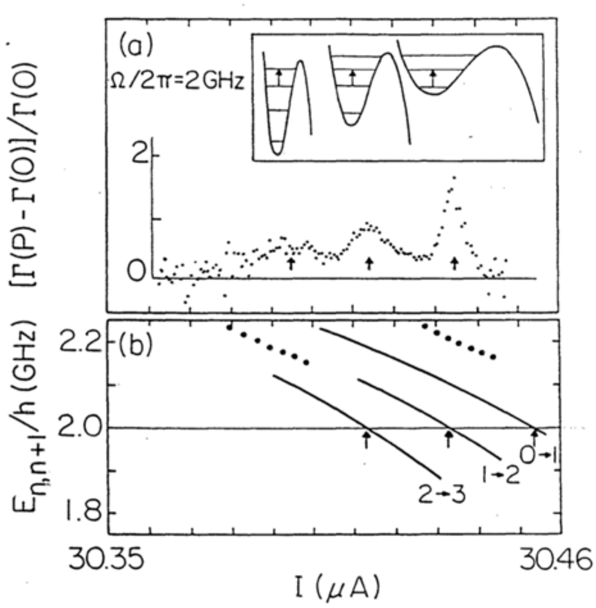

Figure 4*. By irradiating a junction with $f = 2$ GHz microwaves and varying the bias current to change the potential, observations could be made of tunnelling out of the first, second and third excited state, which could be compared quantitatively with straightforward expressions from single particle quantum mechanical calculations. The temperature was high enough for the lower excited levels to be significantly populated $\left(\frac{k_B T}{hf} = 0.29\right)$. This confirms that the macroscopic degree of freedom corresponding to the junction phase difference δ behaves to a very good approximation as a single quantum mechanical particle. (From Fig. 2 in* [12].*)*

Together, these experiments demonstrated beyond a reasonable doubt that a superconducting circuit “big enough to get one’s grubby fingers on” (on page 997 of [6]) could be isolated well enough to observe both energy quantization of a macroscopic degree of freedom as well as macroscopic quantum tunnelling out of a metastable state. In analogy with the tunnelling of an alpha particle out of a heavy nucleus, Clarke *et al.* described their system as a “macroscopic nucleus” and foresaw the possibility of building exotic “macroscopic nuclei with wires” (on page 997 of [6]). As we will see in the next section, this work laid the foundation for exploring macroscopic quantum physics in superconducting circuits, where the Josephson junction plays the role of an engineered artificial atom.

Later developments

In the 1990s, groups in the field explored the conjugate variable to the phase difference, i.e. the charge degree of freedom in both normal and superconducting circuits, while also deepening the understanding of how to control the interaction with the environment. After the invention of Shor's algorithm [14], a quest was started for controllable quantum two-level systems (quantum bits or qubits) as the basis for a quantum computer. Because of the work of the Berkeley group, it was clear that superconducting circuits were one of the possible platforms.

A circuit called a single Cooper pair box with two quantized energy levels differing by the charge of one Cooper pair was explored as a possible qubit [15-16]. The first experiment demonstrating coherent oscillations between the two levels was performed in 1999 by Nakamura, Pashkin and Tsai at Nippon Electric Company (NEC) [17]. These first observed oscillations remained coherent for only 3 ns, but they inspired numerous new designs of superconducting circuits for quantum information processing [18]. In the so-called phase qubit, coherent oscillations between quantized levels in a current biased Josephson junction were observed [19-20]. The readout of this phase qubit used MQT in a similar way as in the 1985 experiment [12]. A major advancement was the introduction of circuit Quantum Electrodynamics (cQED) where the qubit circuit is strongly coupled to a microwave resonator, which in turn is weakly coupled to a transmission line [21-22]. cQED allowed for vast improvement of the coherence time of superconducting qubits and it led to the development of high-fidelity quantum non-demolition readout of the qubit state.

Today, a qubit design called "Transmon" is insensitive to charge noise [23] and used in a number of efforts around the world, aiming to realize a large-scale quantum computer. Here, we note that superconducting circuits is only one among a number of promising technologies used in this global effort.

Beyond qubits, superconducting quantum circuits have impacted the field of quantum optics which traditionally studies the interplay between atoms and the electromagnetic field. Using superconducting circuits, new artificial atoms based on Josephson junctions are designed, allowing for the study of quantum optics in parameter regimes not accessible to atomic physics [24]. Superconducting circuits are also used to probe the quantum nature of other macroscopic solid-state systems [25], such as micromechanical resonators [26] and large spin ensembles. Recently, superconducting circuits placed in a 30-m-long cryostat were used for a loophole-free violation of Bell's inequality [27]. These are only a few of the numerous examples of how macroscopic quantum physics with superconducting circuits has impacted quantum science and played an important role in the formation of a diverse and expanding field of quantum engineering.

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