PHYSICS OF OUR DAYS

PACS numbers: 01.10.Cr, 03.75.Lm, **05.40.–a**, **74.50.+r**

About 2025 Nobel Prize in Physics

V.P. Mineev

DOI: https://doi.org/10.3367/UFNe.2025.10.040053

Abstract. Particle tunneling through the classically forbidden region beneath a potential barrier is a purely quantum-mechanical effect, described in 1928 by George Gamow to explain the finite probability of radioactive alpha decay of nuclei. The same mechanism, associated with Cooper pair tunneling, underlies the Josephson effect — the dissipationless flow of current through a junction between two superconductors. A finite voltage drop, i.e., the destruction of the superconducting state, occurs at currents greater than a certain critical value. The emergence of a dissipative regime is also possible at currents less than the critical value due to jumps in the macroscopic variable of the phase difference of the superconducting states at the junction, which occur due to both the thermally activated mechanism of overcoming the potential barrier and quantum subbarrier tunneling. Experimental studies of the transition between these two mechanisms in an electric circuit with a Josephson junction were awarded the 2025 Nobel Prize in Physics.

Keywords: random processes, tunneling phenomena, Josephson effect

The Nobel Prize in Physics 2025 has been awarded to John Clarke, Michel Devoret, and John Martinis "for the discovery of macroscopic quantum tunnelling and energy quantisation in an electric circuit" [1].

In several studies published in the eighties [2–4], they investigated activation transitions and quantum tunnelling from the zero-voltage state to the resistive state of a current-biased Josephson junction between two superconductors, schematically shown in Fig. 1.

The total current in the circuit is given by the sum of the Josephson current and currents through the resistance and the capacity:

$$J = J_c \sin\varphi + \frac{V}{R} + C\,\frac{dV}{dt}\,. \qquad (1)$$

Taking into account the Josephson relation between the phase difference between two superconductors and the voltage

$$\dot\varphi = \frac{2e}{\hbar}\,V = \frac{2\pi c}{\Phi_0}\,V\,, \qquad (2)$$

V.P. Mineev
Landau Institute for Theoretical Physics, Russian Academy of Sciences,
prosp. Akademika Semenova 1A, 142432 Chernogolovka,
Moscow region, Russian Federation
E-mail: mineev@itp.ac.ru

Received 25 October 2025, revised 28 October 2025
Uspekhi Fizicheskikh Nauk **195** (11) 1232 – 1234 (2025)
Translated by the author

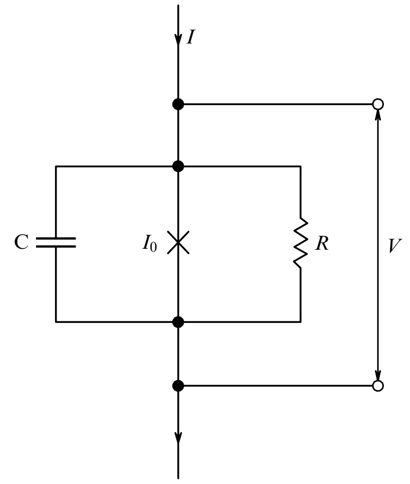

Figure 1. Circuit of Josephson tunnel junction.

equation (1) can be rewritten as

$$\frac{\Phi_0}{2\pi c}\,J = \frac{\Phi_0}{2\pi c}\,J_c \sin\varphi + \frac{1}{R}\left(\frac{\Phi_0}{2\pi c}\right)^2\dot\varphi + C\left(\frac{\Phi_0}{2\pi c}\right)^2\ddot\varphi\,, \qquad (3)$$

which is the equation of motion of a particle with coordinate φ in the potential

$$U(\varphi) = -\frac{\Phi_0}{2\pi c}\,(J\varphi + J_c\cos\varphi)\,, \qquad (4)$$

which looks like a washboard, as shown in Fig. 2. $\Phi_0 = \pi\hbar c/e$ is the flux quantum.

It is clear that, in such a potential, at currents smaller than critical, $J < J_c$, our particle is in a metastable position determined by the equation

$$\varphi_n = \arcsin\frac{J}{J_c} + 2\pi n\,. \qquad (5)$$

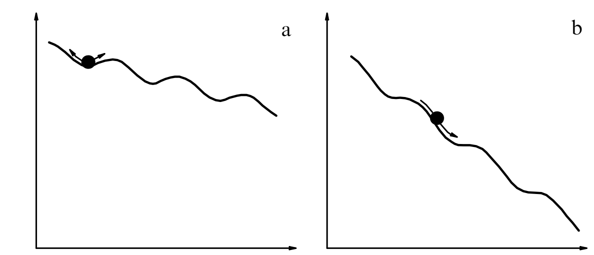

Figure 2. Washboard potential $U(\varphi)$. (a) Particle in stable position. (b) Particle rolling steadily downhill at rate determined by average slope.

Hence,

$$V = \frac{\Phi_0}{2\pi c}\,\dot{\varphi} = 0\,. \qquad (6)$$

At $J > J_c$, the particle is rolling down while oscillating with a time velocity equal on average to

$$\dot{\varphi} = \frac{2e}{\hbar}\,JR = \frac{2e}{\hbar}\,V\,, \qquad (7)$$

which corresponds to a resistive state with an average fall in voltage V.

In addition to the bias current J, there is an additional current $J_f(T)$ due to thermal fluctuations. So, the total current is $J + J_f(T)$. Due to thermal fluctuations, our particle can overcome the potential barrier and roll down to the neighboring metastable minimum. The time τ of escape can be estimated according to the Kramers formula,

$$\tau^{-1} = \frac{\omega_J}{2\pi}\exp\left(-\frac{\Delta U}{T}\right). \qquad (8)$$

The neighboring minima are separated by a potential barrier which, in the case

$$\frac{J_c - J}{J_c} \ll 1\,, \qquad (9)$$

has a height

$$\Delta U = \frac{2^{5/2}}{3}\,\frac{\Phi_0 J_c}{2\pi c}\left(1 - \frac{J}{J_c}\right)^{3/2}. \qquad (10)$$

The pre-exponential factor is a frequency of classical vibrations of a particle in a potential well dependent on the value of the current. Under fulfilment condition (9), it is

$$\omega_J = \left(\frac{2\pi c J_c}{\Phi_0 C}\right)^{1/2}\left[1 - \left(\frac{J}{J_c}\right)^2\right]^{1/4}. \qquad (11)$$

Due to activation processes, the particle can overcome the potential barrier even at bias currents $J < J_c$, which leads to appearance of finite voltage. Thus, the observed critical current J_{co} occurs less than J_c. The average output current increases rapidly with decreasing temperature. Obviously, at $T \to 0$, the time of escape exponentially tends to infinity and the processes for passing through the barrier become ineffective. However, even at zero temperature, there is a finite probability of penetrating through the barrier by means of quantum tunnelling.

John Clarke, together with his PhD student John Martinis and post-doc Michel Devoret from the Centre d'Études Nucléaires de Saclay, France, used an experimental method developed earlier by T.A. Fulton and L.N. Dunkleberger [5]. Here, I cite the Press release of the Nobel Committee for Physics. "The experiments using the current biased Josephson junction 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, 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... .

In their setup [2–4], 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 [2]. 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 characterisation 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."

Let us estimate the temperature of transition from classic to quantum regime penetration through the energy barrier. In the quasi-classic approximation [6], it is

$$\Gamma = \frac{\omega_J}{2\pi}\exp\left(-\frac{2}{\hbar}\int_{\varphi_1}^{\varphi_2} d\varphi\,\left\{2m\left[U(\varphi) - U(\varphi_1)\right]\right\}^{1/2}\right). \qquad (12)$$

Here, $U(\varphi_1) = U(\varphi_0) + \hbar\omega_J/2$, $\varphi_0 = \arcsin(J/J_c)$, φ_2 is the point of potential maximum, $m = C(\Phi_0/2\pi c)^2$. Estimating the integral, we obtain

$$\Gamma = \frac{\omega_J}{2\pi}\exp\left(-a\,\frac{\Delta U}{\omega_J}\right). \qquad (13)$$

Here, a is a number of the order of unity.

Comparing equations (8) and (13) shows that the classic mechanism of penetration through the barrier turns into quantum tunnelling below the temperature

$$T_0 \simeq \omega_J\,. \qquad (14)$$

It can be said that, at $T < T_0$, the processes of overcoming the potential barrier acquire an effective 'exit temperature' of the order of ω_J. Such transitions from the classic to quantum mechanism of penetration through a barrier were first studied by V.I. Gol'danskii in connection with problems of chemical kinetics [7].

A theory of quantum tunneling beyond the semiclassical approximation and taking dissipation into account was developed by A.O. Caldeira and A.J. Leggett [8]. John Clarke and collaborators used an estimate of the effective temperature of quantum tunneling exit based on the Caldeira–Leggett theory [4]. A plot of the exit temperature at

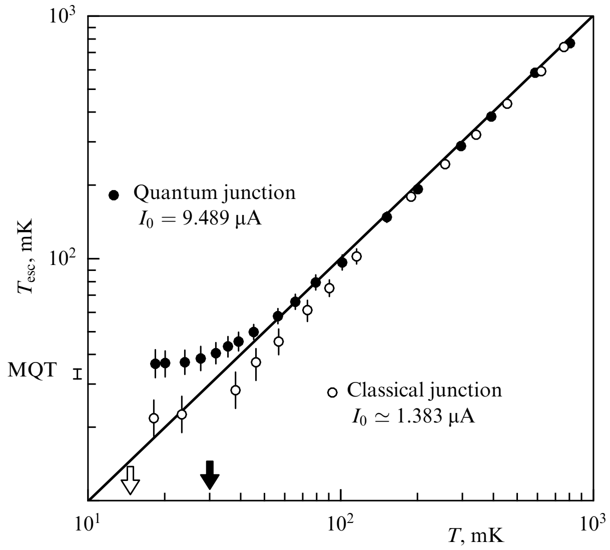

Figure 3. Effective exit temperature, i.e., temperature determining exit velocity, as function of actual temperature with error bars. Black and white arrows indicate predicted transition temperatures between classical and quantum regimes of transition to resistive state for higher and lower critical currents, respectively. Theoretical prediction for exit temperature for macroscopic quantum tunneling (MQT) is marked on ordinate axis [4].

which the transition from the state with $V = 0$ to the resistive state occurs is shown in Fig. 3. Quantum tunneling processes from excited states in a potential well, studied by the same authors, are described in [3].

The discovery of quantum tunneling in a Josephson junction, leading to a transition from a state with $V = 0$ to a resistive state with a finite voltage drop, that is, the discovery of quantum tunneling in the macroscopic world, occurred more than half a century after the discovery of the quantum tunneling mechanism made by George Gamow in 1928 to explain the radioactive alpha decay of nuclei [9].

Following the Nobel Committee's press release [1], let us add several words about later developments. After the work of J. Clarke, M. Devoret, and J. Martinis, it was clear that superconducting circuits were one of the possible platforms for controllable quantum two-level systems (quantum bits or qubits) as the basis for a quantum computer (see review [10]). The first experiment demonstrating coherent oscillations between the two levels was performed in 1999 by Nakamura, Pashkin, and Tsai [11]. These first observed oscillations remained coherent for only 3 ns, but they inspired numerous new designs of superconducting circuits for quantum information processing. In the so-called phase qubit, coherent oscillations between quantized levels in a current biased Josephson junction were observed [12, 13]. The readout of this phase qubit used macroscopic quantum tunnelling in a similar way as in the 1985 experiments of the Nobel laureates. Today, a qubit design called Transmon is insensitive to charge noise [14] and is used in projects around the world, aiming to realize a large-scale quantum computer.

References

1. "The Nobel Prize in Physics 2025: Their experiments on a chip revealed quantum physics in action", Press release. Published: 2025-10-07, https://www.kva.se/en/news/the-nobel-prize-in-physics-2025/
2. Devoret M H, Martinis J M, Esteve D, Clarke J *Phys. Rev. Lett.* **53** 1260 (1984)
3. Martinis J M, Devoret M H, Clarke J *Phys. Rev. Lett.* **55** 1543 (1985)
4. Devoret M H, Martinis J M, Clarke J *Phys. Rev. Lett.* **55** 1908 (1985)
5. Fulton T A, Dunkleberger L N *Phys. Rev. B* **9** 4760 (1974)
6. Ivanchenko Yu M, Zil'berman L A *Sov. Phys. JETP* **28** 1272 (1969); *Zh. Eksp. Teor. Fiz.* **55** 2395 (1968)
7. Gol'danskii V I *Sov. Phys. Dokl.* **4** 1172 (1959); *Dokl. Akad. Nauk SSSR* **124** 1261 (1959)
8. Caldeira A O, Leggett A J *Ann. Physics* **149** 374 (1983)
9. Gamow G *Nature* **122** 805 (1928)
10. Makhlin Yu, Schön G, Shnirman A *Rev. Mod. Phys.* **73** 357 (2001)
11. Nakamura Y, Pashkin Yu A, Tsai J S *Nature* **398** 786 (1999)
12. Yu Y et al. *Science* **296** 889 (2002)
13. Martinis J M et al. *Phys. Rev. Lett.* **89** 117901 (2002)
14. Koch J et al. *Phys. Rev. A* **76** 042319 (2007)