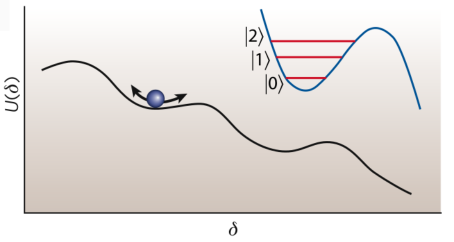
Macroscopic charge tunneling in superconducting structures: remarks on Nobel Prize in Physics 2025

Tadeusz Domański

M. Curie-Skłodowska University
L U B L I N



NCBJ

Warszawa, 8 December 2025

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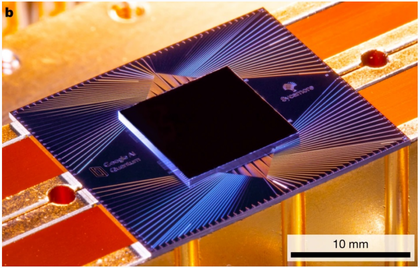

NCBJ **Warszawa, 8 December 2025**

OUTLINE

- **Josephson effect**

  [Nobel Prize in Physics 1973]

- **Macroscopic tunneling & quantization**

  [Nobel Prize in Physics 2025]

- **Technological applications**

  [superconducting qubits & processors]

- **Current challenges**

  [topological states in Josephson junctions]

SUPERCONDUCTOR

Basic properties:

1. **perfect conductor**

2. **perfect diamagnet**

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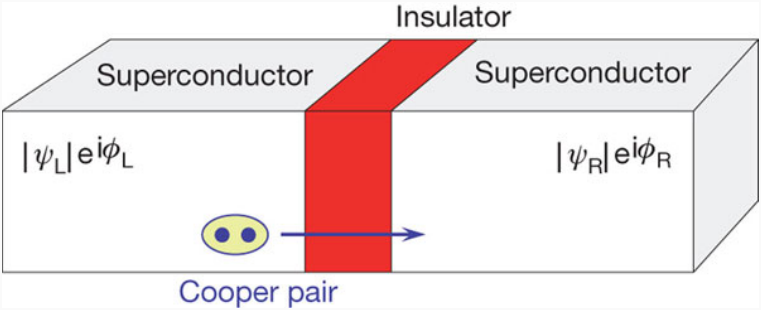
Such Bose-Einstein condensate of the Cooper pairs is described by the macroscopic wave function:

$$\Psi(\vec{r},t) \equiv |\Psi(\vec{r},t)| \; e^{i\phi(\vec{r},t)}$$

JOSEPHSON EFFECT

Two superconductors, differing in phase $\phi_L \neq \phi_R$, contacted through a narrow insulating region induce the *super*flow of Cooper pairs.



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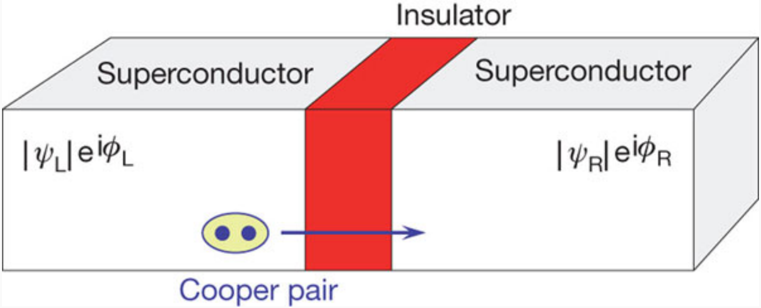

This effect has been predicted by B.D. Josephson in 1962.

/ 22-year-old PhD student at Cambridge, England /

HYDRODYNAMIC REASONING

In quantum mechanics the probability current is defined by

$$\vec{j}(\vec{r},t) = -\frac{i\hbar}{2m}\left[\Psi^\star(\vec{r},t)\nabla\Psi(\vec{r},t) - \Psi(\vec{r},t)\nabla\Psi^\star(\vec{r},t)\right]$$

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Applying this formalism to the wave-function Φ_0 of Cooper pairs

$$\Psi_0(\vec{r},t) \equiv \underbrace{\left|\Psi_0(\vec{r},t)\right|}_{\sqrt{n(\vec{r},t)}}\ e^{i\phi(\vec{r},t)}$$

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we can express the Josephson current density

$$\vec{j}_J(\vec{r},t) = -\,q\,\frac{i\hbar}{2m}\left[\Psi_0^\star\nabla\Psi_0 - \Psi_0\nabla\Psi_0^\star\right]$$

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where $q = 2e$ is charge and $\vec{v}(\vec{r},t)$ is velocity of Cooper pairs.

EXPERIMENTAL EVIDENCE

VOLUME 10, NUMBER 6 PHYSICAL REVIEW LETTERS 15 MARCH 1963

PROBABLE OBSERVATION OF THE JOSEPHSON SUPERCONDUCTING TUNNELING EFFECT

P. W. Anderson and J. M. Rowell
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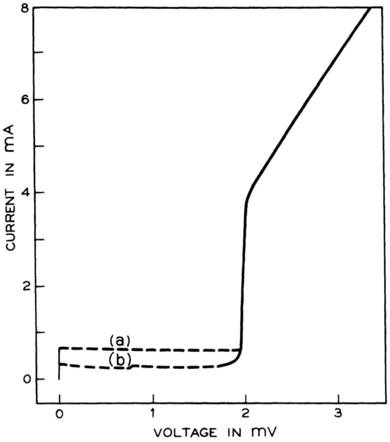
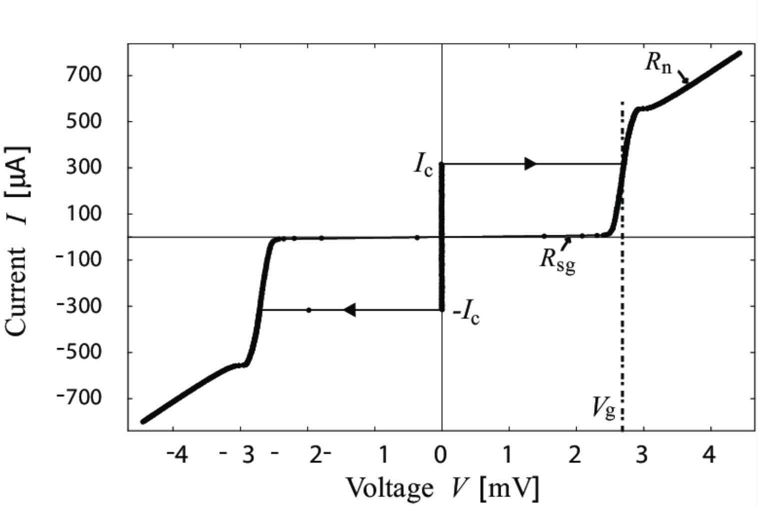


Authors reported:

„dc tunneling current at or near zero voltage in very thin tin oxide barriers between superconducting Sn and Pb"

I(V) CHARACTERISTICS

Typical current-voltage plot, where $V_g = 2\Delta$



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2025

J. Clarke, M.H. Devoret, J.M. Martinis

RECIPIENTS OF NOBEL PRIZE 2025

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

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

Michel H. Devoret

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John M. Martinis

Prize share: 1/3

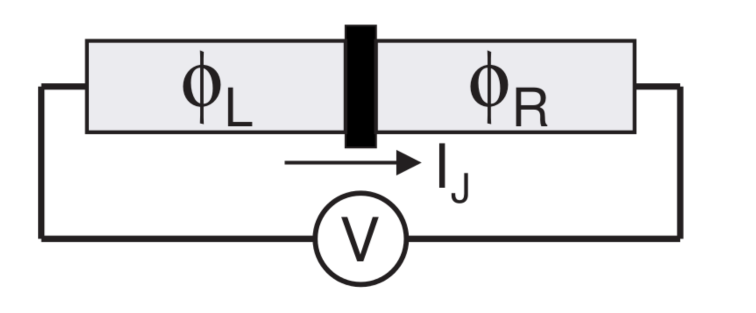
John Clarke - emeritus at the University of California (Berkeley)

Michel D. Devoret - University of California (Santa Barbara) & Yale University

John M. Martinis - University of California (Santa Barbara)

JOSEPHSON EQUATIONS

Let's consider the Josephson junction enclosed in electric circuit



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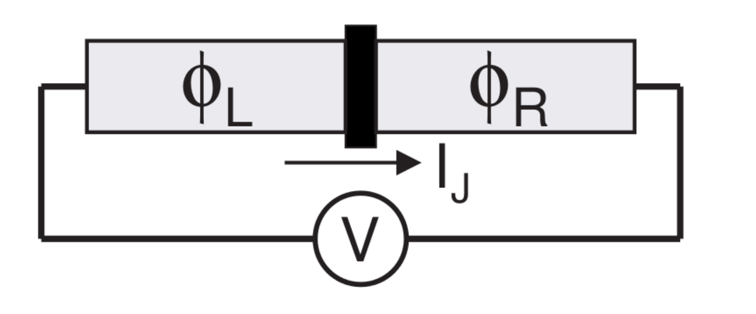

with the macroscopic wave-functions $\Psi_{L/R}$ of the Cooper pairs

$$\Psi_{L/R} \equiv |\Psi_{L/R}| \; e^{i\phi_{L/R}}$$

where $|\Psi_{L/R}| = \sqrt{n_{L/R}}$ denote concentrations and $\phi_{L/R}$ phases.

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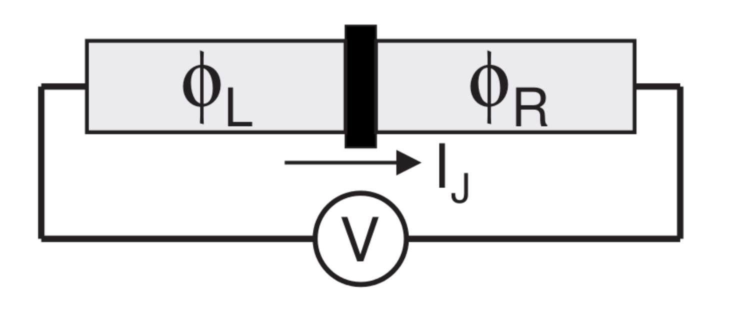

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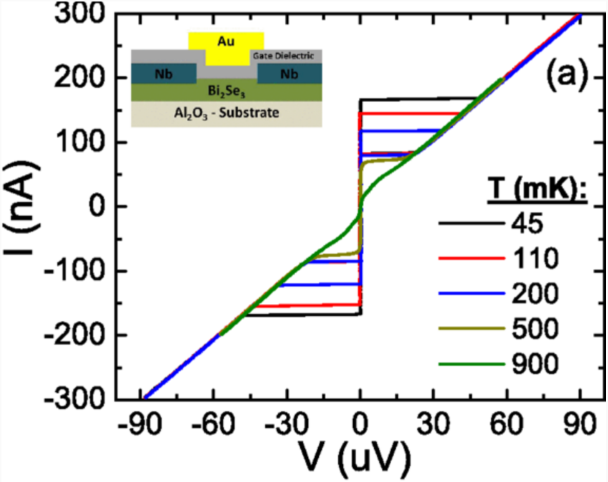
where $\left|\Psi_{L/R}\right| = \sqrt{n_{L/R}}$ denote concentrations and $\phi_{L/R}$ phases.

$$I_J = I_{crit} \sin\left(\phi_R - \phi_L\right)$$

RESISTIVE TRANSITION

The critical current I_{crit} diminishes upon increasing temperature.



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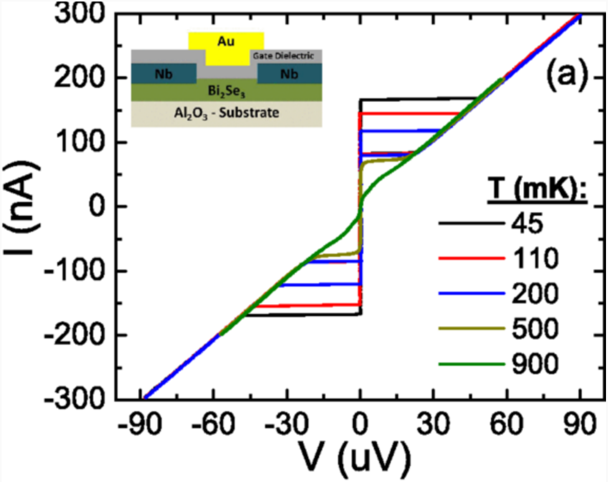
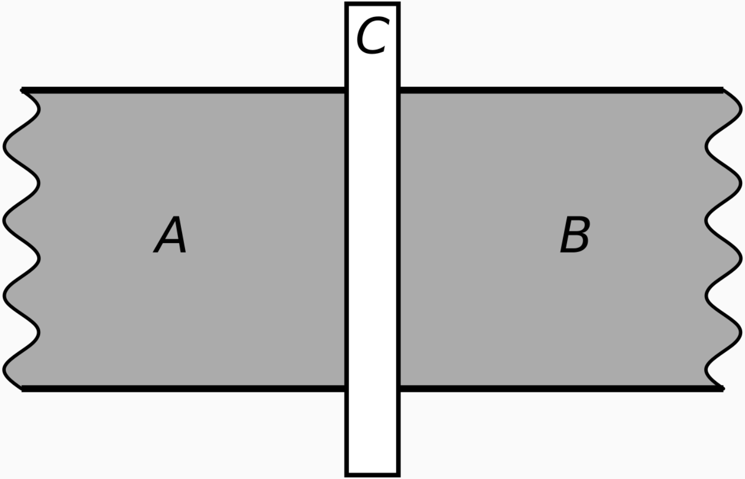


At $I \to I_{crit}$ the Josephson superflow changes to resistive behaviour.

JOSEPHSON EQUATIONS

Let's denote two sides of this junction by A and B, correspondingly



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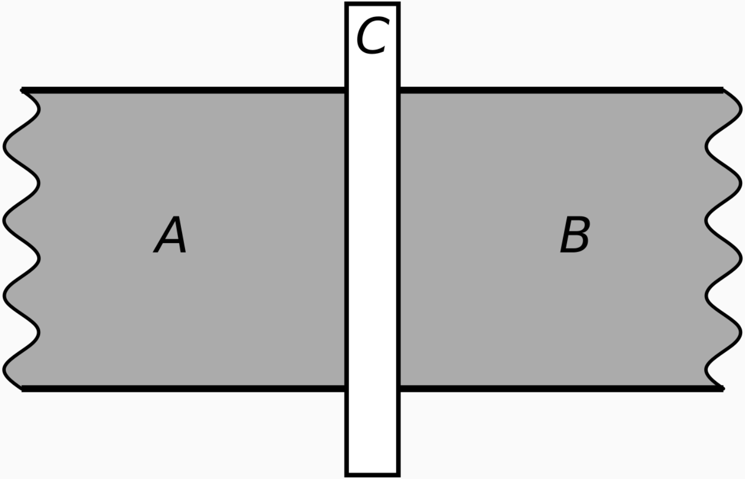

and assume that voltage V is applied across the junction.

Schrödinger eqn $i\hbar\frac{\partial\Psi_{A/B}}{\partial t} = \hat{H}\Psi_{A/B}$ for the Josephson junction:

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix} = \begin{pmatrix}eV & K\\ K & -eV\end{pmatrix}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix} \tag{1}$$

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To solve this equation (1), let us first calculate the time derivative for the wave function of superconductor A:

$$\frac{\partial}{\partial t}(\sqrt{n_A}e^{i\phi_A}) = \dot{\sqrt{n_A}}e^{i\phi_A} + \sqrt{n_A}(i\dot{\phi}_A e^{i\phi_A})$$

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Schrödinger eqn gives:

$$(\dot{\sqrt{n_A}} + i\sqrt{n_A}\dot{\phi}_A)e^{i\phi_A} = \frac{1}{i\hbar}(eV\sqrt{n_A}e^{i\phi_A} + K\sqrt{n_B}e^{i\phi_B})$$

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$$\dot{\sqrt{n_A}} + i\sqrt{n_A}\dot{\phi}_A = \frac{1}{i\hbar}(eV\sqrt{n_A} + K\sqrt{n_B}e^{i\varphi}) \qquad (2)$$

and (its complex conjugate):

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By addying eqns (2,3) we eliminate $\dot{\phi}_A$

$$2\dot{\sqrt{n_A}} = \frac{1}{i\hbar}(K\sqrt{n_B}e^{i\varphi} - K\sqrt{n_B}e^{-i\varphi}) = \frac{K\sqrt{n_B}}{\hbar} \cdot 2\sin\varphi$$

and using $\dot{\sqrt{n_A}} = \frac{\dot{n}_A}{2\sqrt{n_A}}$, we finally obtain:

$$\dot{n}_A = \frac{2K}{\hbar}\sqrt{n_A n_B}\ \sin\varphi.$$

Now, by subtracting eqns (2,3) we eliminate $\dot{\sqrt{n_A}}$:

$$2i\sqrt{n_A}\dot{\phi}_A = \frac{1}{i\hbar}(2eV\sqrt{n_A} + K\sqrt{n_B}e^{i\varphi} + K\sqrt{n_B}e^{-i\varphi})$$

which gives:

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Similar equations can be derived for superconductor B:

$$\begin{aligned} \dot{n}_B &= -\frac{2K\sqrt{n_A n_B}}{\hbar}\sin\varphi \\ \dot{\phi}_B &= \frac{1}{\hbar}(eV - K\sqrt{\frac{n_A}{n_B}}\cos\varphi) \end{aligned}$$

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Tunneling current is thus: $I_A = 2e\dot{n}_A = -I_B \propto \sin(\varphi)$

In particular, for $n_A \approx n_B$ this treatment yields:

$$I = I_c \sin(\varphi) \tag{4}$$

$$\frac{\partial \varphi(t)}{\partial t} = \frac{2eV}{\hbar} \tag{5}$$

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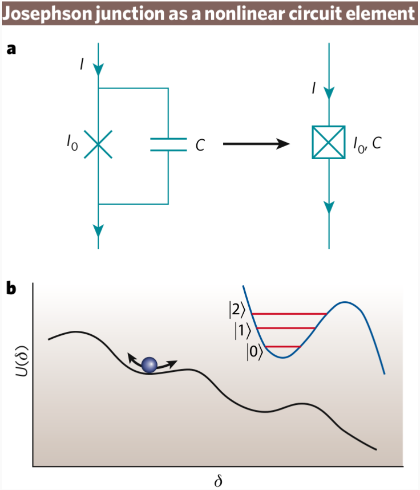
Set of these Josephson equations:

(4) relates the tunneling current I through a junction to the macroscopic phase difference φ (it can be static)

(5) gives the time evolution φ in terms of the voltage V across a junction (dc Josephson effect)

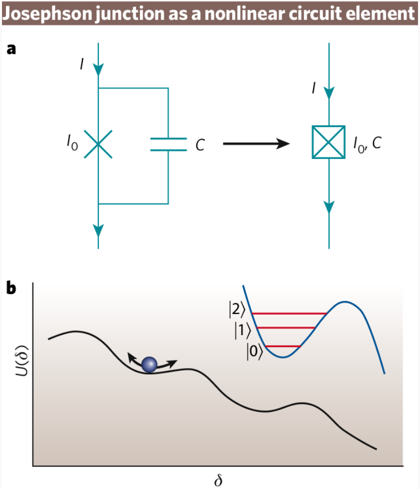
JOSEPHSON JUNCTION + CAPACITOR



Incorporating the Josephson junction into ciruit with capacitor:

$$I(t) = I_c \sin(\varphi(t)) + \frac{\hbar}{2e} C \frac{\partial^2 \varphi}{\partial t^2}$$

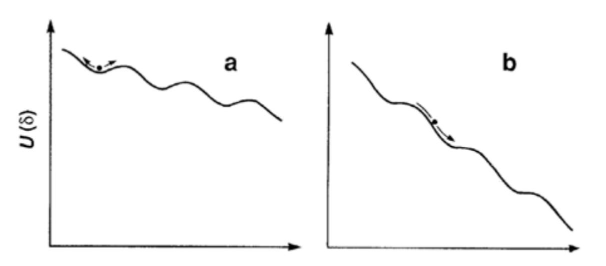
JOSEPHSON JUNCTION + CAPACITOR



This setup has effectively the „washboard potential"

$$U(\varphi) = -I_0 \frac{\hbar}{2e}\varphi - E_J \cos\varphi$$

Influence of the washboard potential $U(\delta) = -I_0 \frac{\hbar}{2e}\delta - E_J \cos\delta$



Josephson phase [δ]

In absence of fluctuations and/or external fields

$\Longrightarrow$ the system „stays” in a local minimum (in zero-voltage state), oscillating with the plasma ω_p

SUPERCONDUCTING CIRCUIT

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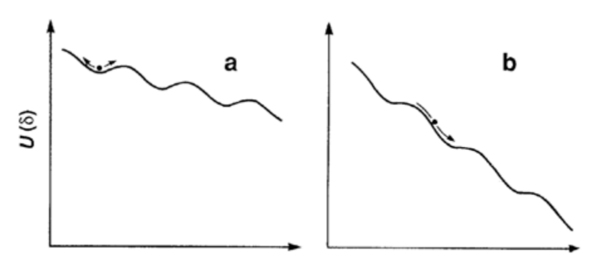

Josephson phase [δ]

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$\Longrightarrow$ the system „stays" in a local minimum (in zero-voltage state), oscillating with the plasma ω_p

$\Longrightarrow$ for $I > I_{crit}$ the system „runs" down the washboard $\langle \frac{d}{dt}\delta \rangle > 0$, switching to the resistive state

QUANTUM-NESS OF MACROSCOPIC SYSTEMS

Supplement of the Progress of Theoretical Physics, No. 69, 1980

Macroscopic Quantum Systems and the Quantum Theory of Measurement

A. J. LEGGETT

School of Mathematical and Physical Sciences
University of Sussex, Brighton BN1 9QH

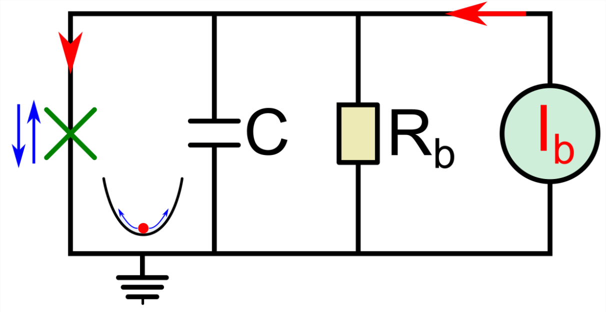
(Received August 27, 1980)

This paper discusses the question: How far do experiments on the so-called "macroscopic quantum systems" such as superfluids and superconductors test the hypothesis that the linear Schrödinger equation may be extrapolated to arbitrarily complex systems? It is shown that the familiar "macroscopic quantum phenomena" such as flux quantization and the Josephson effect are irrelevant in this context, because they correspond to states having a very small value of a certain critical property (christened "disconnectivity") while the states important for a discussion of the quantum theory of measurement have a very high value of this property. Various possibilities for verifying experimentally the existence of such states are discussed, with the conclusion that the most promising is probably the observation of quantum tunnelling between states with macroscopically different properties. It is shown that because of their very high "quantum purity" and consequent very low dissipation at low temperatures, superconducting systems (in particular SQUID rings) offer good prospects for such an observation.

A.J. Leggett, Prog. Theor. Phys. 69, 80 (1980).

QUANTUM-NESS OF JOSEPHSON CIRCUIT

Setup:



Phase difference φ of the Josephson junction and charge Q on the capacitor represent canonically conjugated quantities, which are subject to the Heisenberg's uncertainty principle:

QUANTUM-NESS OF JOSEPHSON CIRCUIT

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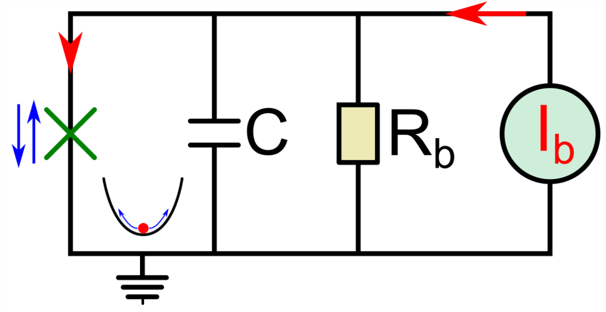

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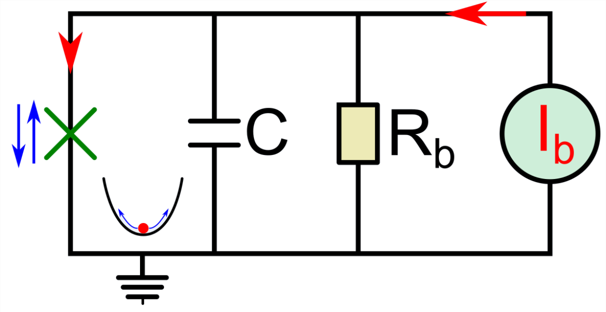

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- **for $E_J \ll (2e)^2/2C$ the charge Q is well defined**

MACROSCOPIC TUNNELING & QUANTIZATION

VOLUME 55, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1985

Energy-Level Quantization in the Zero-Voltage State of a Current-Biased Josephson Junction

John M. Martinis, Michel H. Devoret,[(a)] and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 14 June 1985)

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VOLUME 55, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1985

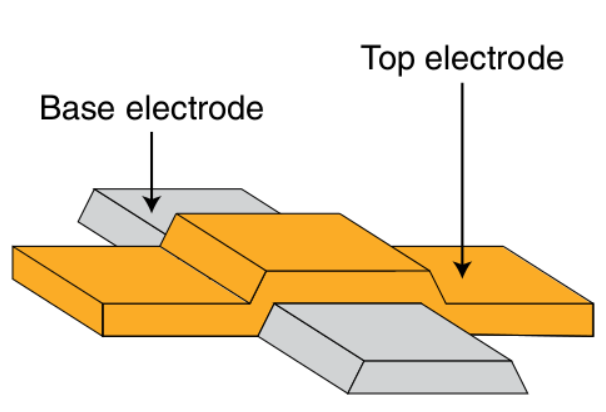
Measurements of Macroscopic Quantum Tunneling out of the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 26 July 1985)

The escape rate of an underdamped ($Q \approx 30$), current-biased Josephson junction from the zero-voltage state has been measured. The relevant parameters of the junction were determined *in situ* in the thermal regime from the dependence of the escape rate on bias current and from resonant activation in the presence of microwaves. At low temperatures, the escape rate became independent of temperature with a value that, with no adjustable parameters, was in excellent agreement with the zero-temperature prediction for macroscopic quantum tunneling.

EXPERIMENTAL SETUP

Josephson junction used by J.M. Martinis, M.H. Devoret and J. Clarke

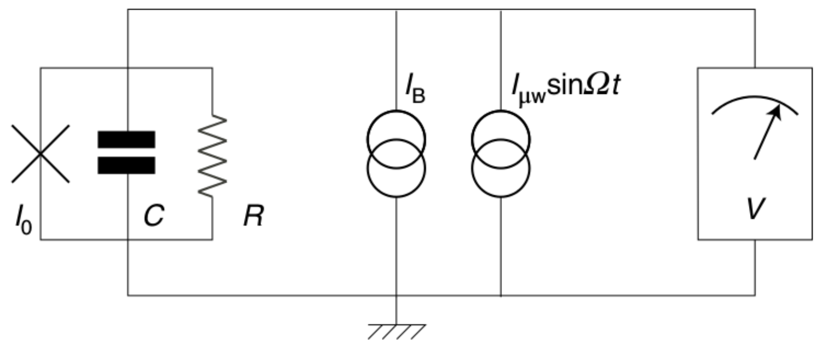


Device size:
10 μm $\times$ 10 μm

Superconducting Nb (base electrode) and PbIn alloy (top electrode) separated by 1-nm thick NbO_x (insulating layer) which was formed by plasma-oxidation.

EXPERIMENTAL SETUP

Electric circuit used by J.M. Martinis, M.H. Devoret and J. Clarke



Josephson junction (cross) shunted by a capacitance (C) and resistance (R) connected to both the static bias I_B and microwave $I_{\mu w}$ current sources.

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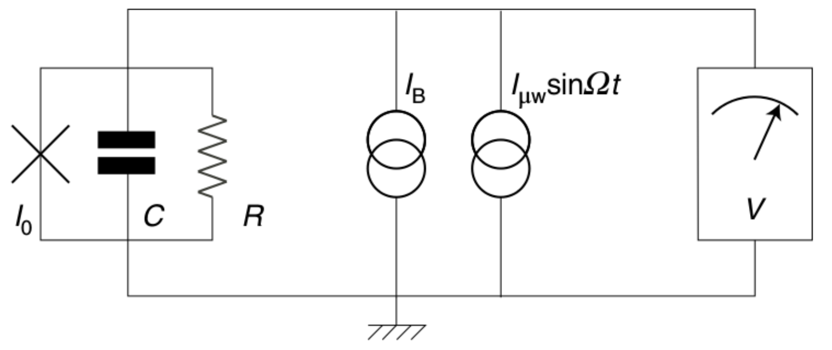

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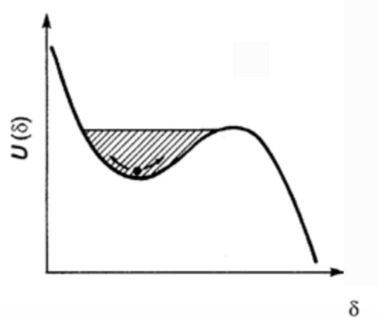
Voltage V across the junction was measured by a low-noise audio-frequency amplifier.

1. MACROSCOPIC TUNNELING: IDEA

Characteristic values: ω_p - plasma frequency, ΔU - potential barrier



Empirical method for probing the escape rate from a local mimimum:

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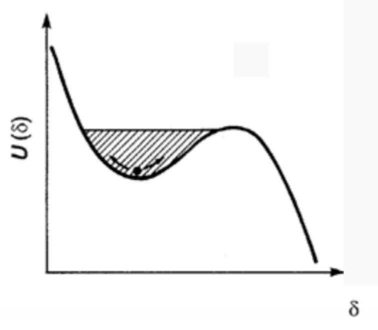

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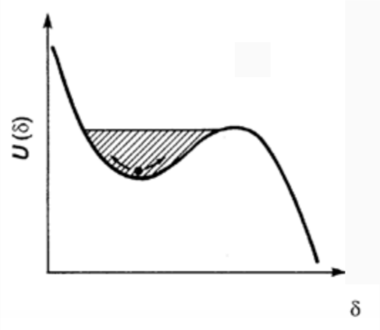

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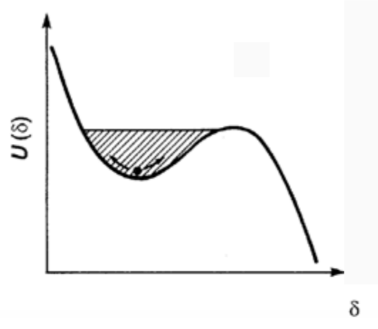

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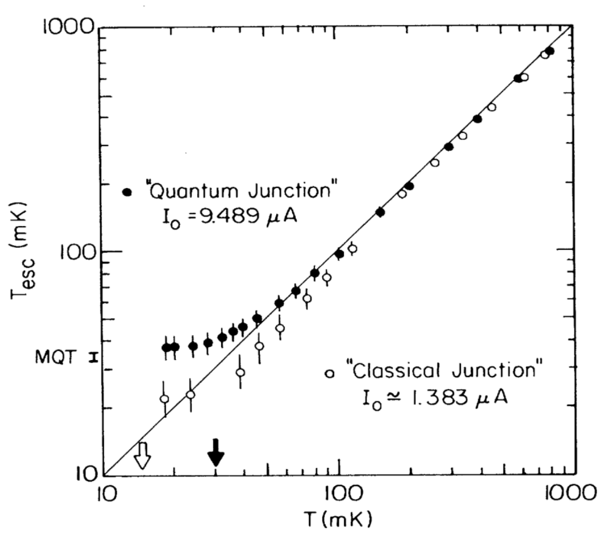
$\Longrightarrow$ A.O. Caldeira and A. Leggett, Ann. Phys. (N.Y.) 149, 374 (1983).

1. MACROSCOPIC TUNNELING: RESULTS

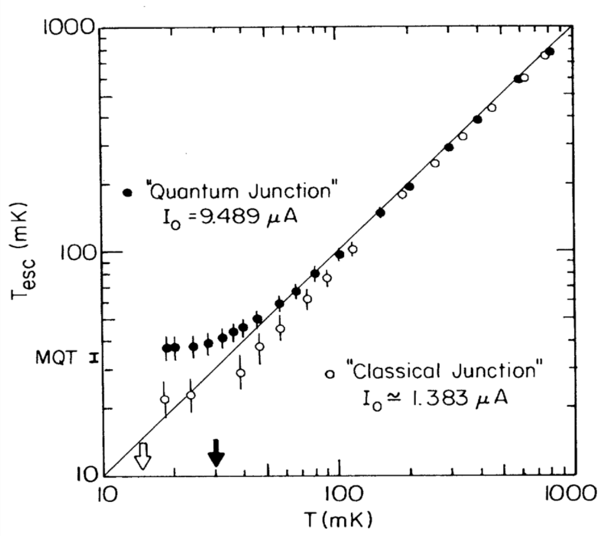
The measured "escape temperature" T_{esc} from the local minimum



Phys. Rev. Lett. 55, 1908 (1985).

1. MACROSCOPIC TUNNELING: RESULTS

The macroscopic quantum tunneling occurs at: $T \leq 30$ mK.



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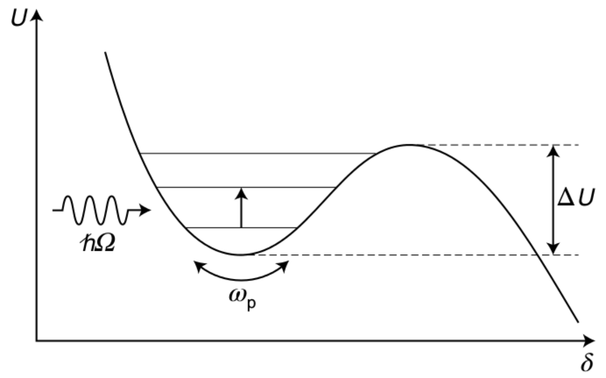
Empirical method for probing (detecting) the quantized energy levels:



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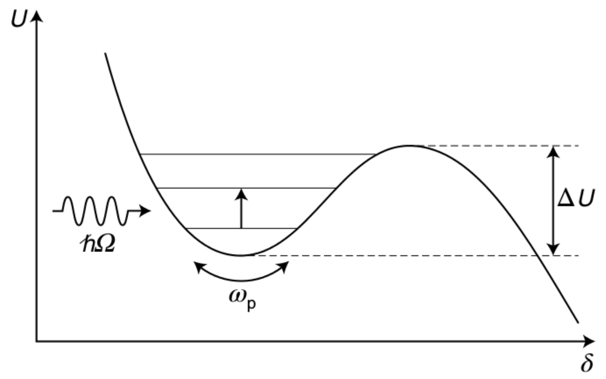

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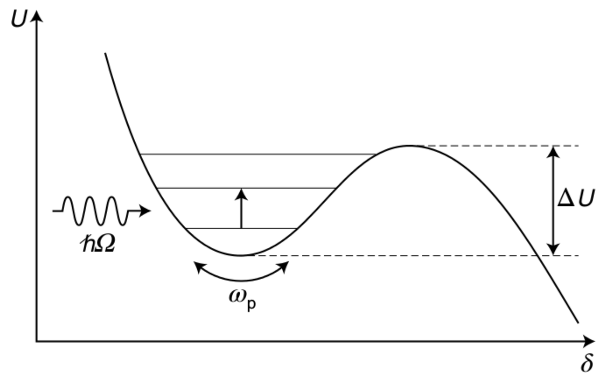

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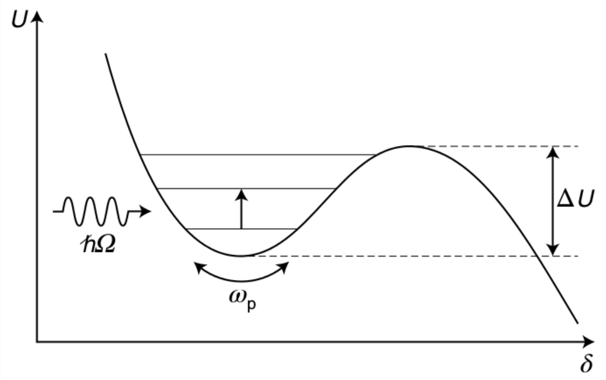

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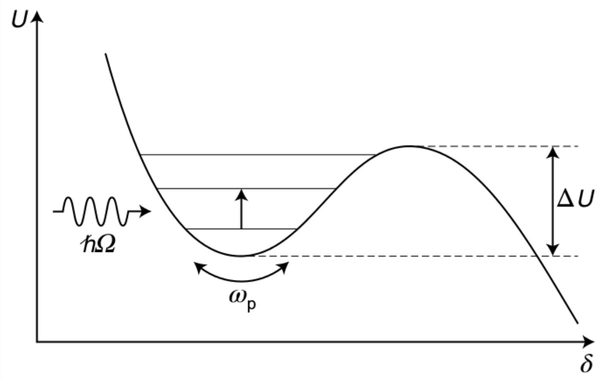

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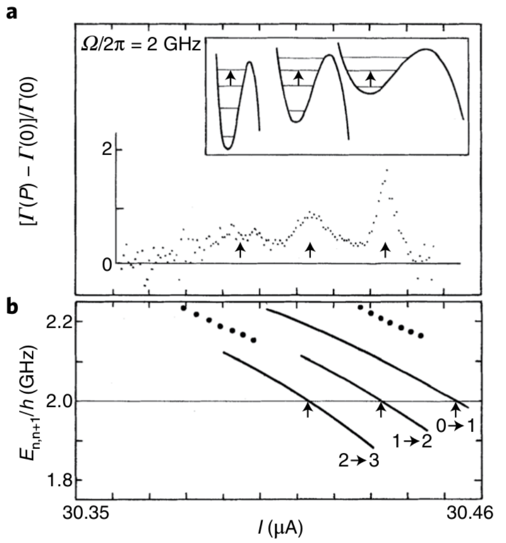
- **force the inter-level transition $E_n \to E_{n+1}$**
- **observe the thermal escape rate from the excited level E_{n+1}**

2. ENERGY QUANTIZATION: RESULTS

Inter-level transitions induced by the microwaves $\Omega = 2$ GHz at $T = 28$ mK.



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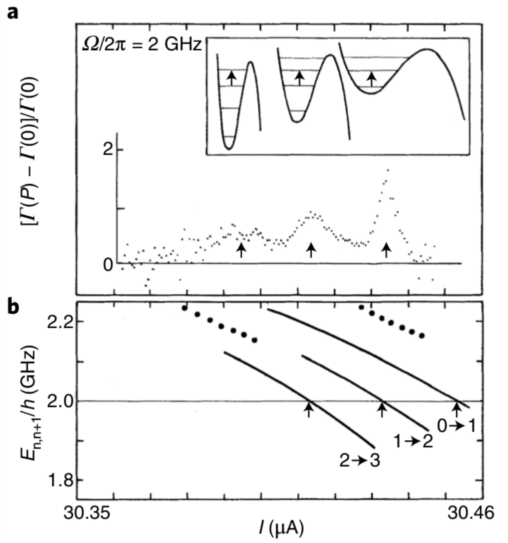
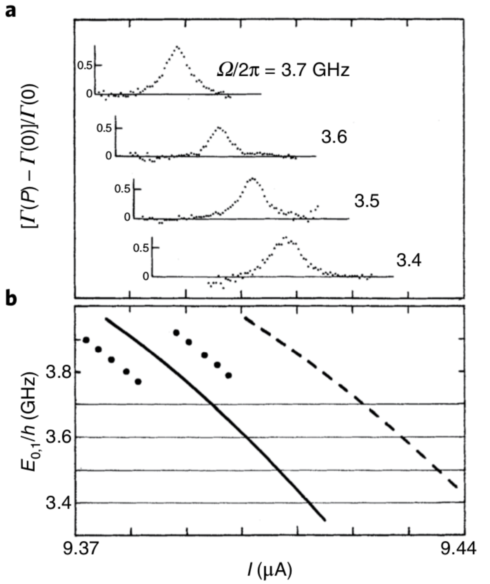


Arrows indicate positions of the resonances (bottom pannel shows the calculated results).

2. ENERGY QUANTIZATION: RESULTS

Transition $E_0 \to E_1$ induced by the microwaves $\Omega = 3.4, 3.5, 3.6, 3.7$ GHz.



Quantum bits

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based on Josephson junctions

$\Rightarrow$ **The next step in the demonstration of macroscopic quantum physics was to implement devices showing the superposition of two quantum states.**

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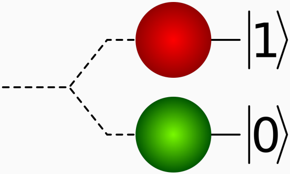

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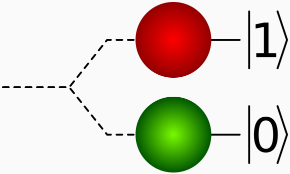
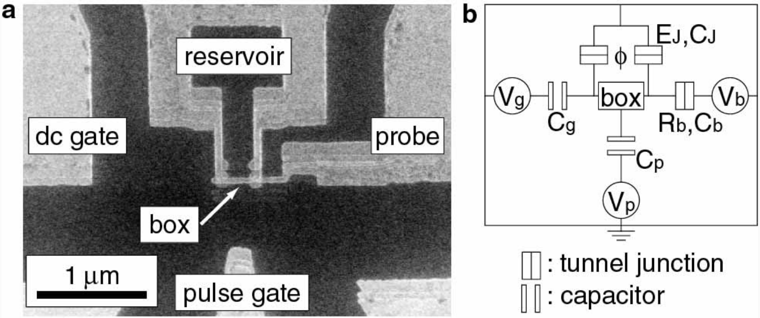


⇒ **Such idea was first considered by A. Leggett in the 1980s in his discussion about macroscopic quantum coherence in superconducting devices**

SUPERCONDUCTING QUBIT: FIRST REALIZATION

Y. Nakamura et al carried out the first experiment on charge qubit,



Y. Nakamura, Y.A. Pashkin, J.S. Tsai, Nature 398, 786 (1999).

showing a superposition of the Cooper-pair states $|n\rangle$ and $|n+1\rangle$, where n is the number of electron pairs (in the Cooper-pair-box).

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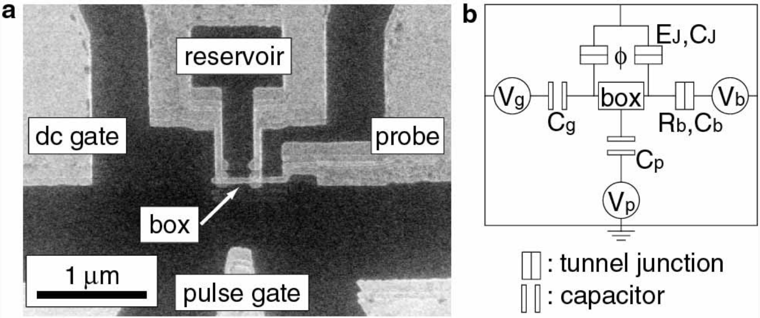

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showing a superposition of the Cooper-pair states $|n\rangle$ and $|n+1\rangle$, where n is the number of electron pairs (in the Cooper-pair-box).

$\Rightarrow$ The quantum state was controlled by gate potential, hence gatemon.

SUBSEQUENT ACTIVITIES

Realizations of superconducting quantum bits:

$\Longrightarrow$ **(2000) flux qubit** **(J. Friedman et al, C. van der Wal et al)**

/superconducting loop interrupted by one or three Josephson junctions/

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$\Longrightarrow$ (later) many other ...

Schematic idea of the Josephson phase qubit (phason).

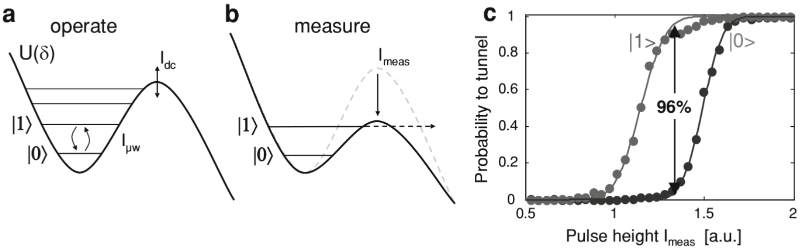


Fig. 1 **a** Plot of non-linear potential $U(\delta)$ for the Josephson phase qubit. The qubit states $|0\rangle$ and $|1\rangle$ are the two lowest eigenstates in the well. The junction bias I_{dc} is typically chosen to give 3–7 states in the well. Microwave current $I_{\mu w}$ produces transitions between the qubit states. **b** Plot of potential during state measurement. The well barrier is lowered with a bias pulse I_{meas} so that the $|1\rangle$ state can rapidly tunnel. **c** Plot of tunneling probability versus I_{meas} for the states $|0\rangle$ and $|1\rangle$. The arrow indicates the optimal height of I_{meas}, which gives a fidelity of measurement close to the maximum theoretical value 96%

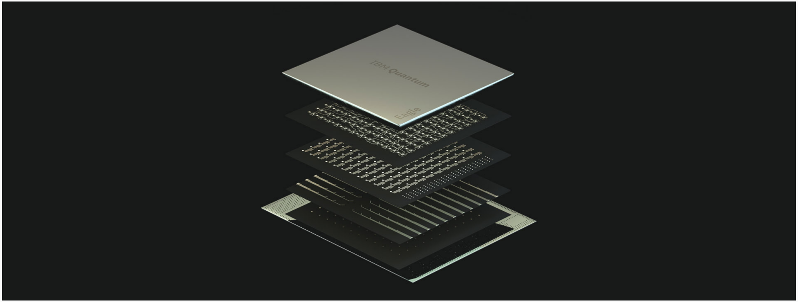
J.M. Martinis, Quantum Inf Process 8, 81-103 (2009).

Quantum processors

Quantum processors

based on superconducting qubits

In November 2021 IBM informed about construction of 127-qubit superconducting processor Eagle.



https://postquantum.com/industry-news/ibm-eagle/

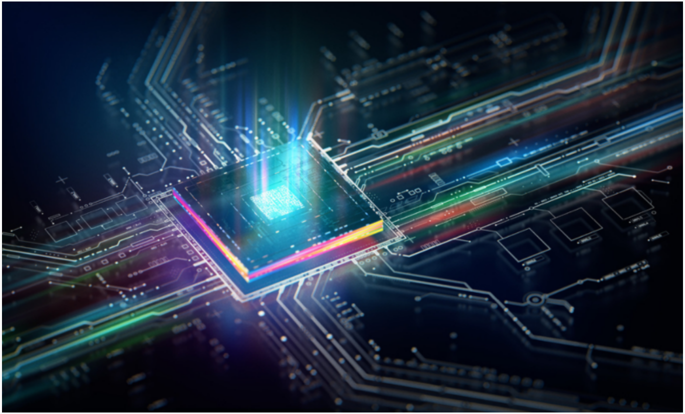
SUPERCONDUCTING PROCESSOR: WILLOW

In December 2024 Google demonstrated 105-qubit processor based on superconducting qubits (transmons).

Google Quantum AI and collaborators, Nature 638, 920 (2024).

SUPERCONDUCTING PROCESSOR: WILLOW

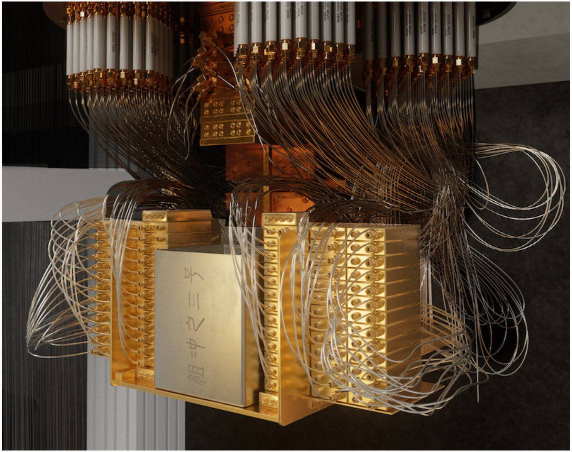
Simulation of the probability distribution obtained in 5 minutes by processor Willow would take about 10^{25} years by the fastest classical computer.



H. Neven (Google blog, 9 December 2024).

SUPERCONDUCTING PROCESSOR: ZUCHONGZHI 3.0

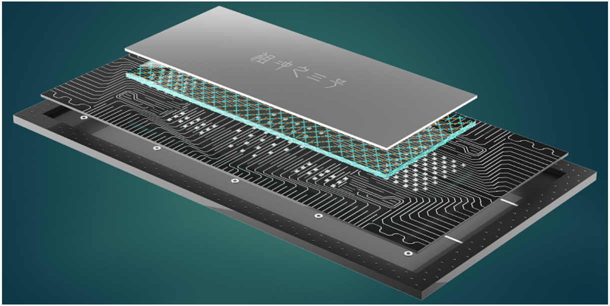
105-qubit processor constructed by the group of prof. Jian-Wei Pan (University of Science and Technology, China)



D. Gao et al, Phys. Rev. Lett. 134, 090601 (2025).

SUPERCONDUCTING PROCESSOR: ZUCHONGZHI 3.0

Simulation of the probability distribution obtained in 100 seconds by processor Zuchongzhi 3.0 would take at least several 10^6 years by the fastest classical computer.



Zuchongzhi 3.0 processor consists of 105 qubits: 15 qubits in 7 arrays.

D. Gao et al, Phys. Rev. Lett. 134, 090601 (2025).

PRESENT & FUTURE APPLICATIONS

Superconducting quantum circuits can address the challenges associated with:

- ⋆ **sensing spins, phonons, and exotic particles**
- ⋆ **quantum communication between different chips or subsystems**
- ⋆ **transduction between microwave and optical photons**
- ⋆ **simulations of many-body systems**
- ⋆ **and computations of test algorithms**

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$\Longrightarrow$ **For details see:**

J.M. Marinis, M.H. Devoret, J. Clarke, Nature Phys. 16, 234 (2020).

SUMMARY

$\Rightarrow$ **Unquestionable facts:**

1. superconducting qubits based on Josephson junctions

(gatemon, transmon, fluxonium, Xmon, Unimon, ...)

2. superconducting quantum processors

(Google, IBM, Intel, IMEC, BBN Technology, Rigetti)

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2. superconducting quantum processors

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⇒ **Challenges:**

⋆ **topological qubits & processors**

(protection, braiding of Majorana quasiparticles, ...)

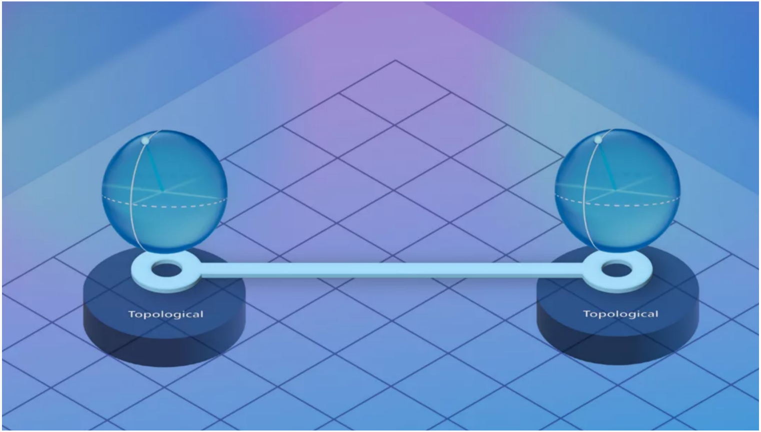
Topological quantum computer

(superconducting qubits based on parity)

TOPOLOGICAL QUBIT

Topological superconducting qubit based on:

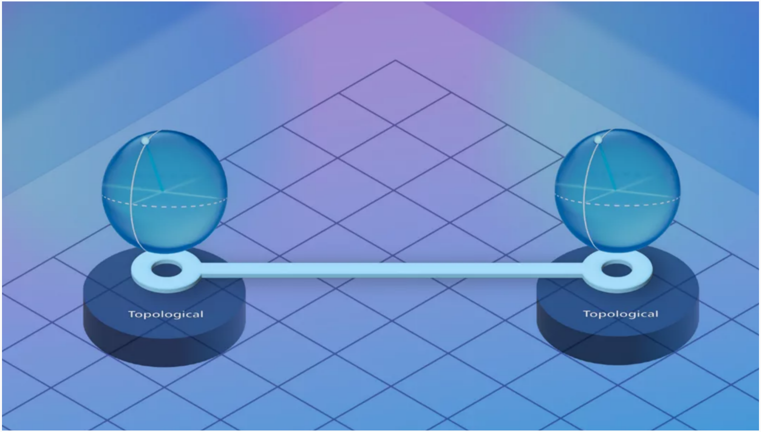
$\Rightarrow$ **Majorana quasiparticles**



TOPOLOGICAL QUBIT

Topological superconducting qubit based on:

⇒ **Majorana quasiparticles**

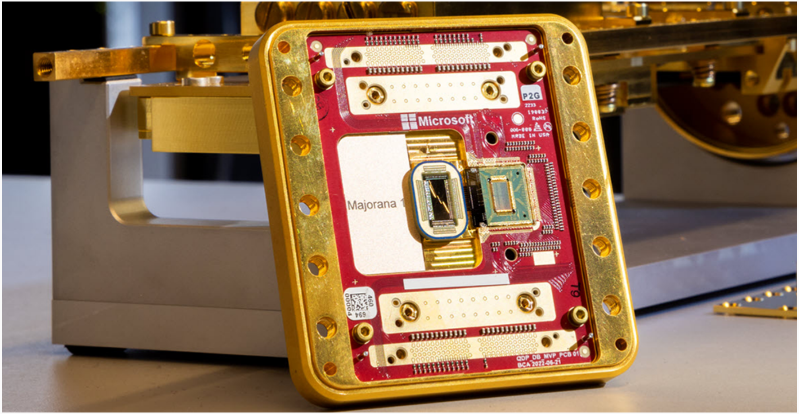


Such qubits would have:

⇒ **topological protection against environmental influence.**

RECENT NEWS

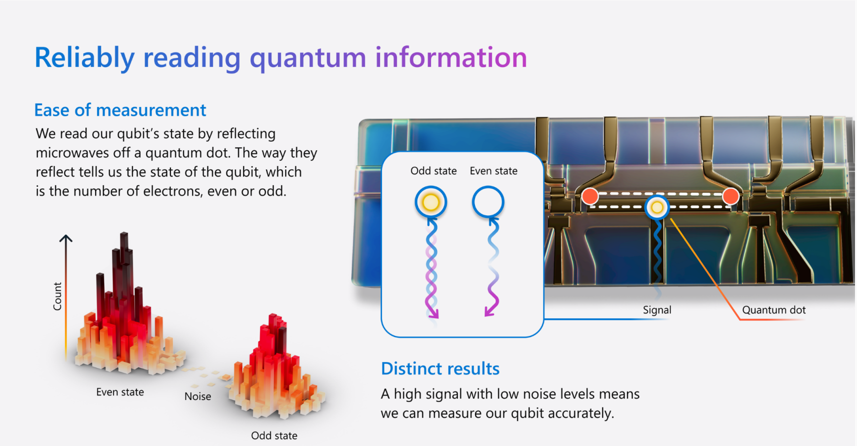
In February 2025 Microsoft informed about construction of the first processor based on topological superconducting qubits



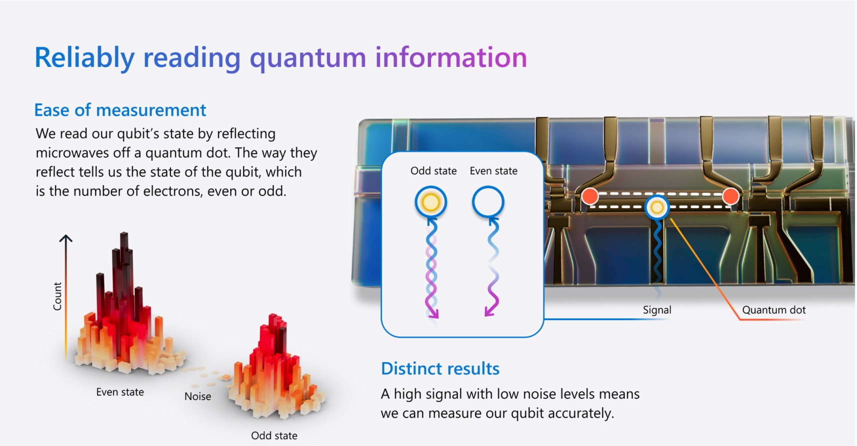
Microsof Azure Quantum, Nature 638, 651 (2025).

https://www.youtube.com/shorts/jPrl2wO1GfM

CONTROVERSIES



"Tetron" device in the shape of H-letter, consisting of four Majorana quasiparticles



"Tetron" device in the shape of H-letter, consisting of four Majorana quasiparticles

Parity measurement was announced during APS March Meeting (14 000 participants) but the scientific community expressed high scepticism.

M. Rini, Physics 18, 68 (2025).

Thank You

Thank You

https://sites.google.com/view/domanskit/lectures

SUPERCONDUCTING QUANTUM BIT

Measurement of Rabi oscillations. The measurement probability of the $|1\rangle$ state is plotted versus microwave pulse length. Pulse sequence consists of a microwave pulse of variable time, tuned to the qubit transition frequency, followed by a measurement pulse, as depicted in the inset. The energy decay time for this qubit is $T_1 = 600$ ns.