The Nobel Prize in Physics 2025 for John Clarke, Michel H. Devoret and John Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

Nobel Prize in Physics 2025

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

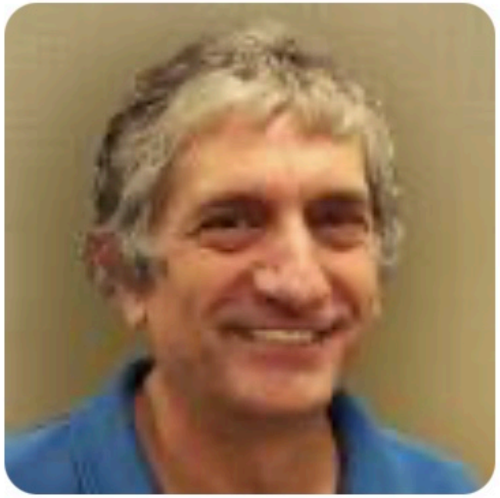
John M. Martinis

Prize share: 1/3

The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

[https://www.nobelprize.org/prizes/physics/2025/summary/]

The Laureates...

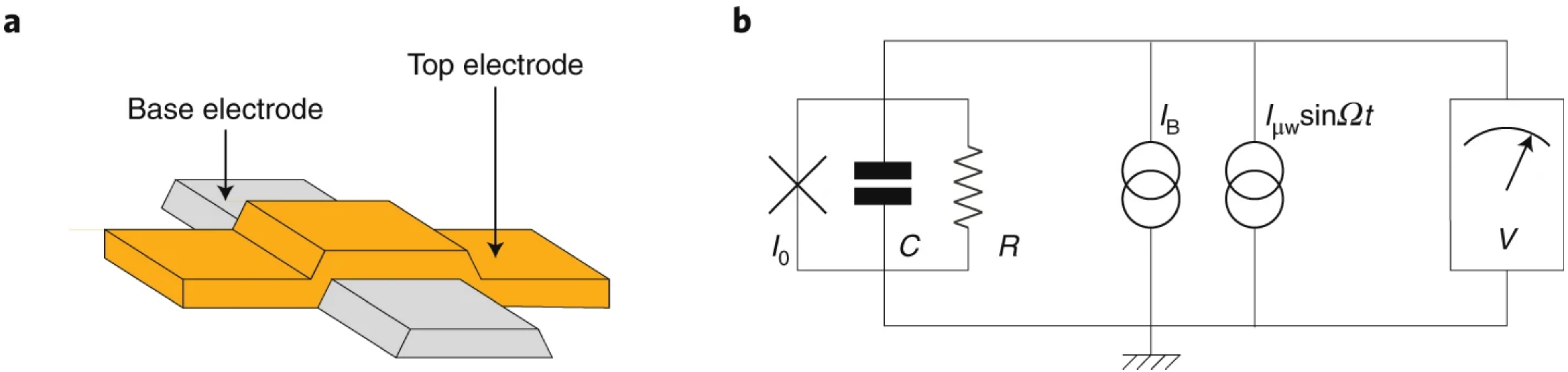


John M. Martinis

Michel Devoret

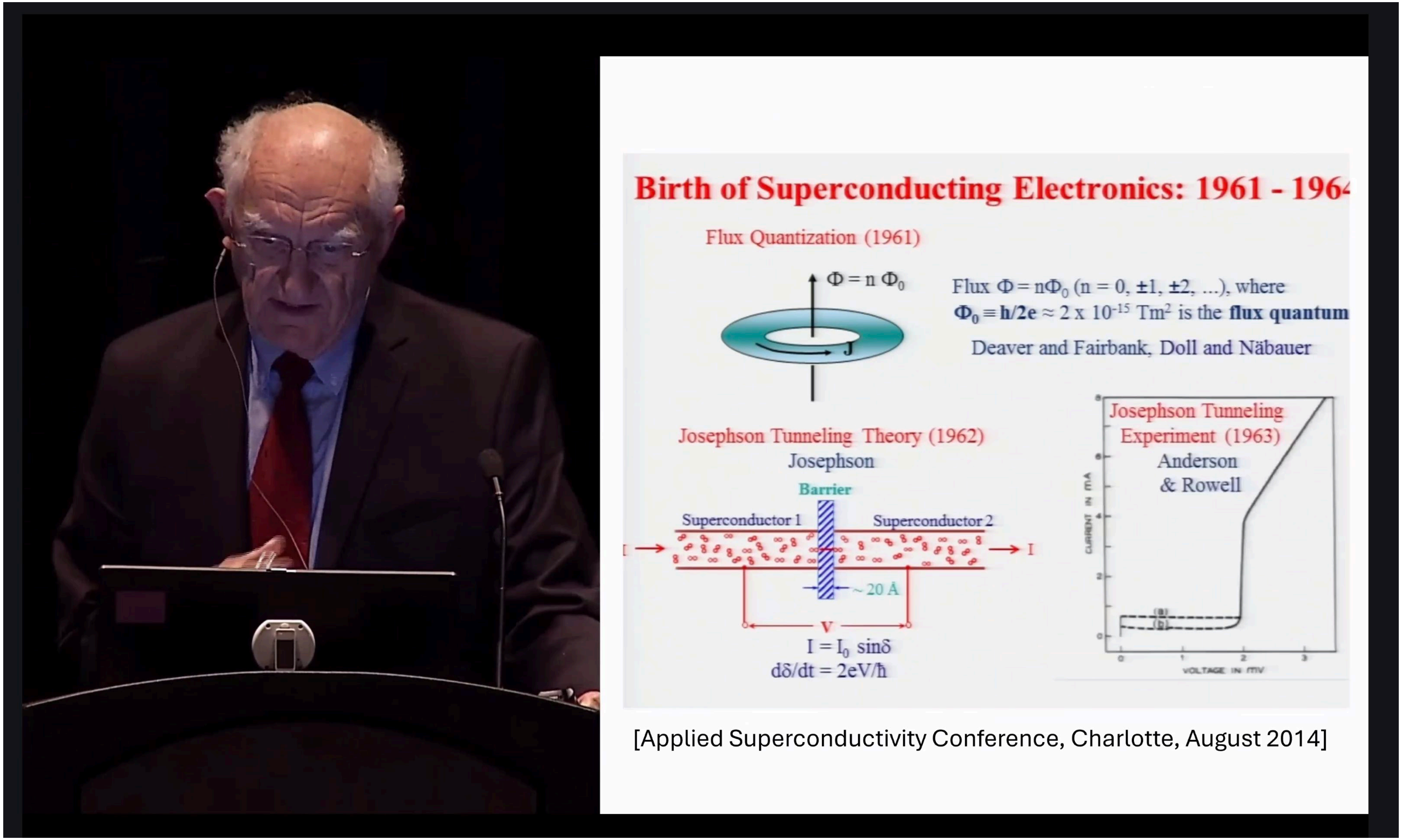
John Clarke

… and *The Device* they build



a, Schematic of a cross-strip Josephson superconducting tunnel junction. Our devices consist of a Nb base electrode and a top PbIn alloy electrode separated by a ~1-nm thick Nb-oxide layer formed by plasma-oxidation of the base electrode. **b**, Circuit schematic of a Josephson element (cross) shunted by a capacitance C and resistance R, and connected to both static bias (I_B) and microwave ($I_{\mu w}$) current sources. The voltage V across the junction is measured by a low-noise audio-frequency amplifier chain represented symbolically. Panel **b** adapted with permission from ref. [2], APS.

[from: *Martinis, Devoret, Clarke, Nature Physics* ***16****, 234–237 (2020)*]



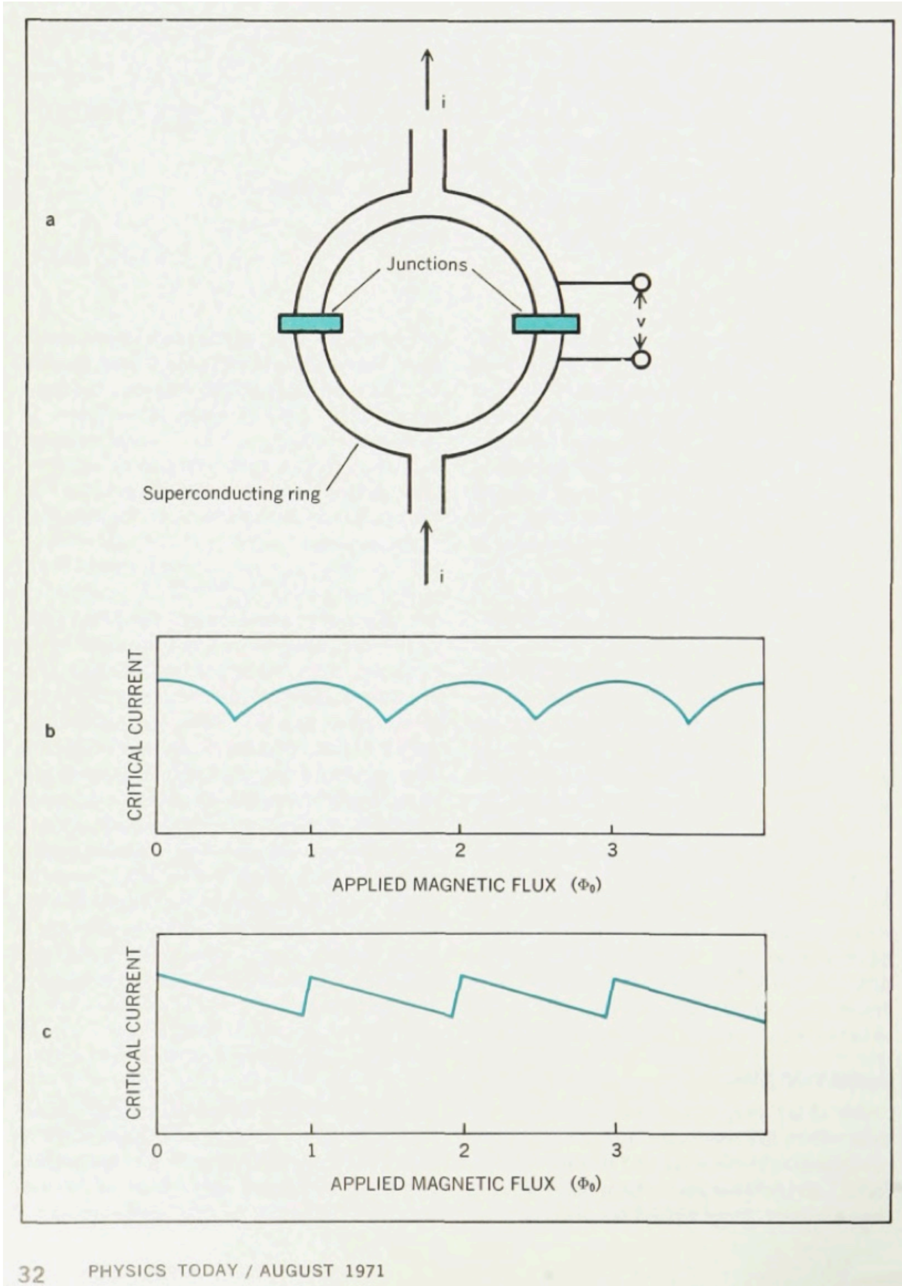
[Applied Superconductivity Conference, Charlotte, August 2014]

John Clarke (b.1942)

— leading expert on SQUIDs
(= ***S****uperconducting* ***QU****antum*
I*nterference* ***D****evice*)
[*Clarke, Physics Today* ***24****, 30 (1971)*]

— In 1975, wrote a visionary paper:
Application of Josephson junctions to computer storage and logic elements and to magnetic measurements
[*AIP Conf. Proc., 1975, (29), 17*]

—In 1970s studied *the flicker 1/f noise* (aka *the pink noise*)
[***'1/f noise' in music and speech,*** *Voss & Clarke, Nature 258, 317 (1975)*]



Superconductivity–related Noble prizes

1913 — *Heike Kamerlingh Onnes,* for investigations on the properties of matter at low temperatures

1972 — *John Bardeen, Leon Cooper, Robert Schrieffer* the BCS theory of superconductivity

1973 — *Leo Esaki, Ivar Giaever, Brian Josephson* (33yo!) tunneling phenomena in semiconductors and superconductors; predictions for a supercurrent through a tunnel barrier

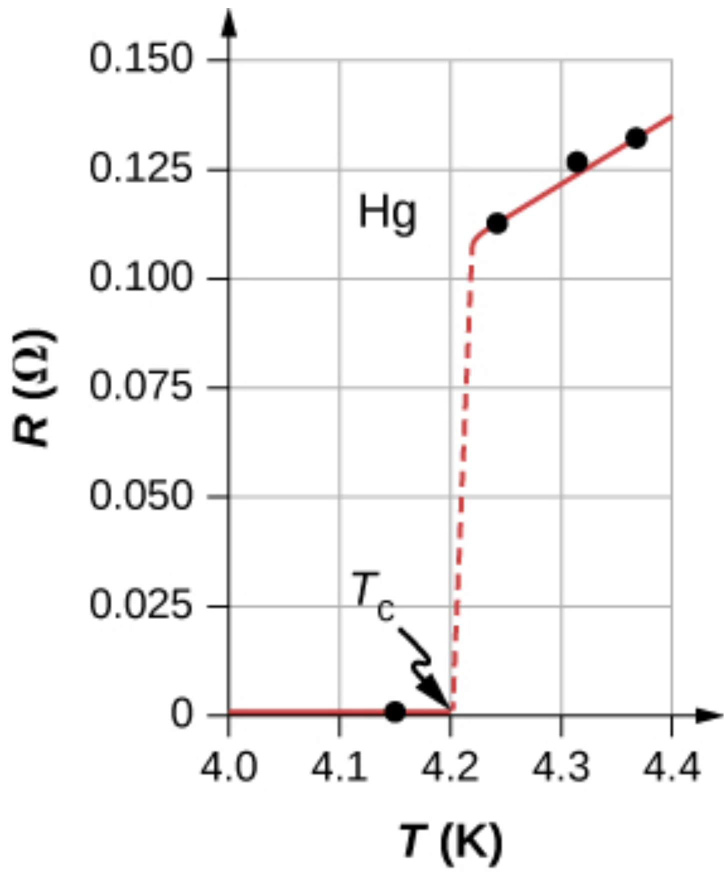
1987 — *Georg Bednorz and K. Alex Müller* the discovery of high-temperature superconductivity

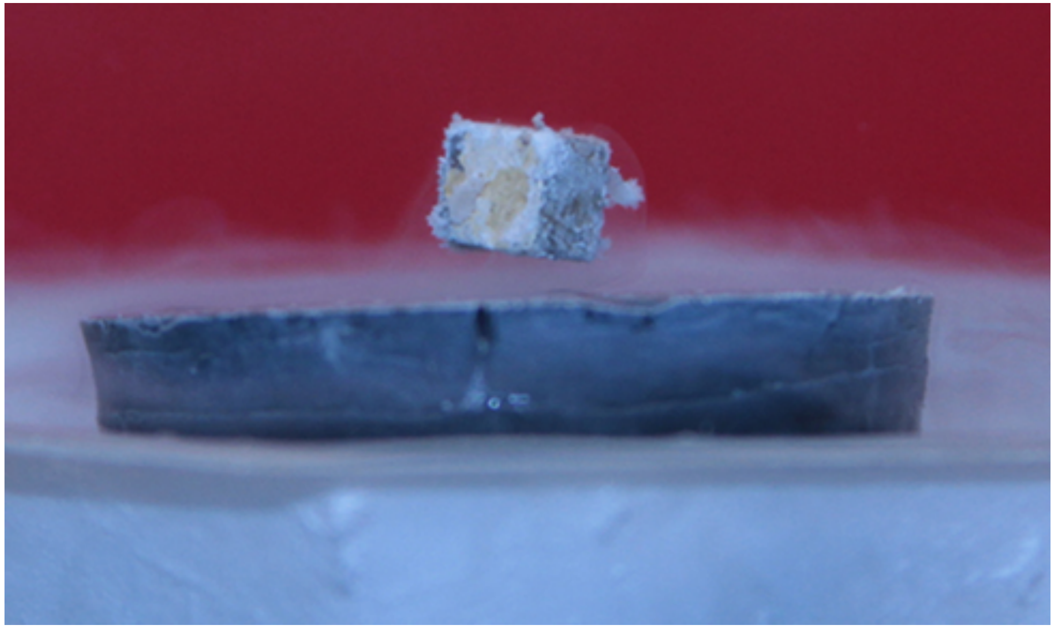
2003 — *Alexei Abrikosov, Vitaly Ginzburg, and Anthony Leggett* theories on superconductors

[2016 — *David J. Thouless, Duncan Haldane, John M. Kosterlitz*
theoretical discoveries of topological phase transitions
$\Longrightarrow$ later link to superconductivity]

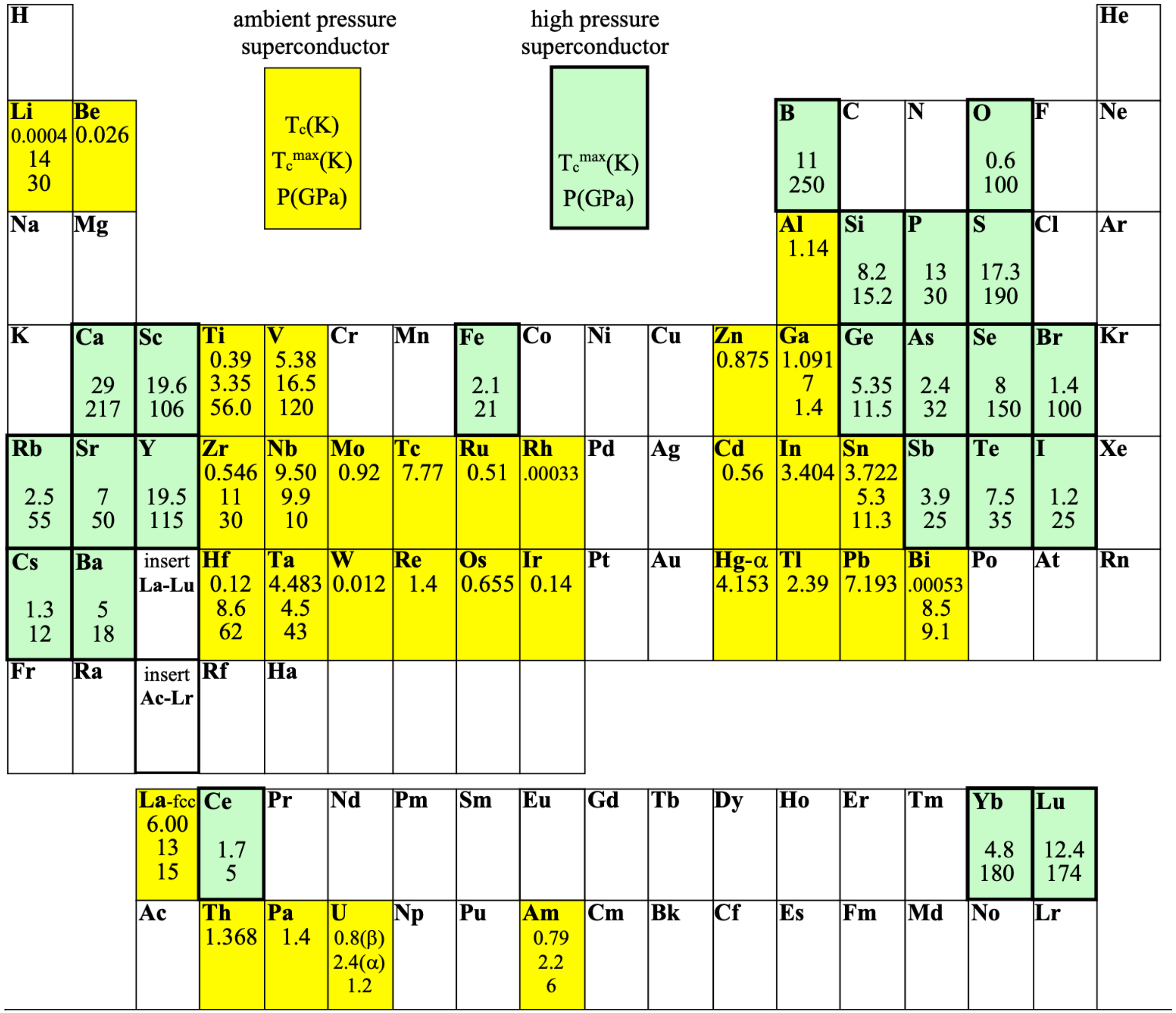
2025 — *John Clarke, Michel Devoret, and John Martinis*
demonstrating macroscopic quantum phenomena in superconducting circuits

Superconductivity = Zero resistance + Meissner effect



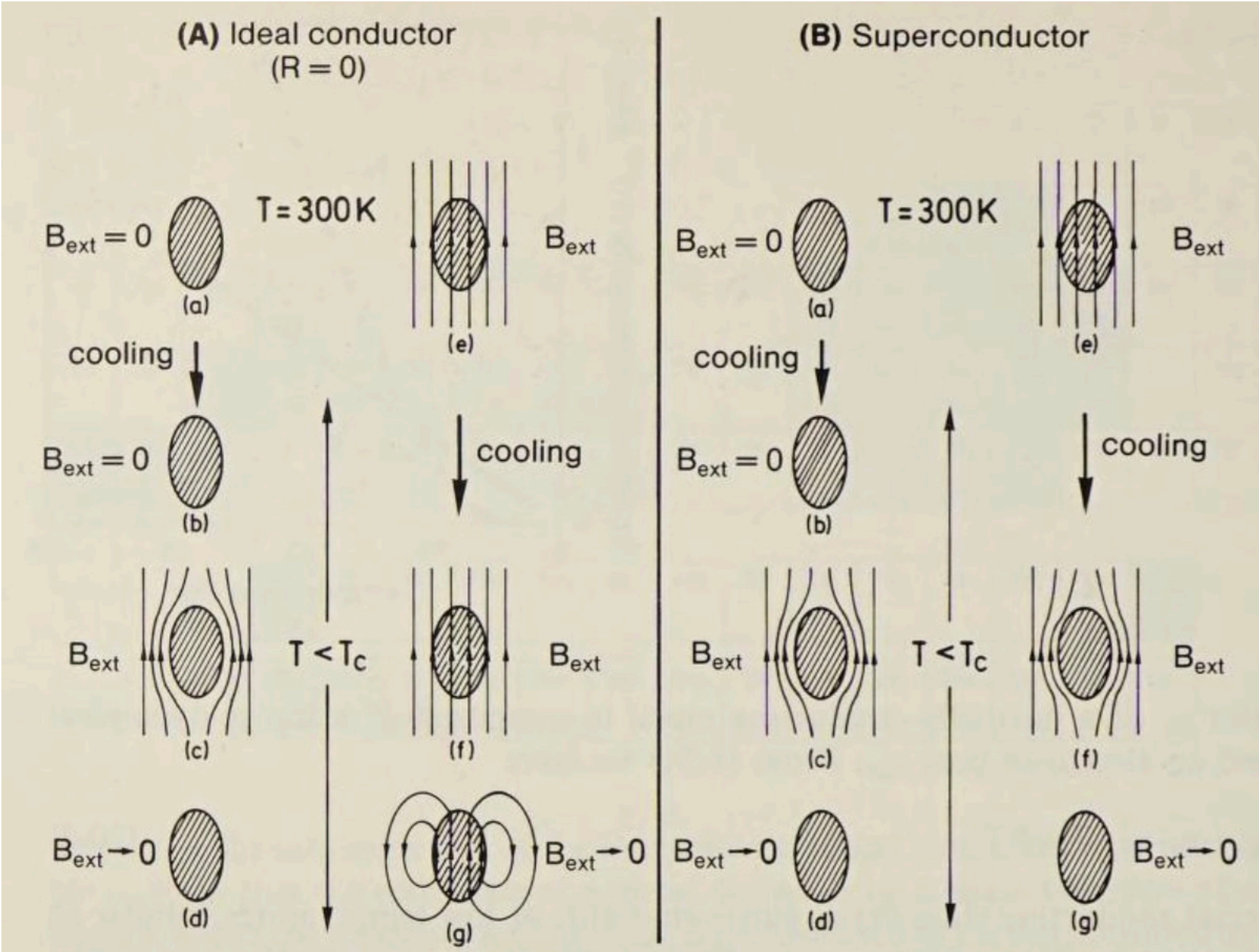


Left: Resistance of mercury — *H. K. Onnes* (1911). ***Right***: Small magnet levitates over a superconductor [*from* phys.libretext.org]



[*From:* *web.physics.wustl.edu*, ca. 2017]

$\Longrightarrow$ A superconductor is not just "a perfect conductor"...



[From: Ibach, Lüth, *Solid-state physics*, Springer-Verlag, NY 1991]

Type I– vs type II– (*aka* high-T_c) superconductor

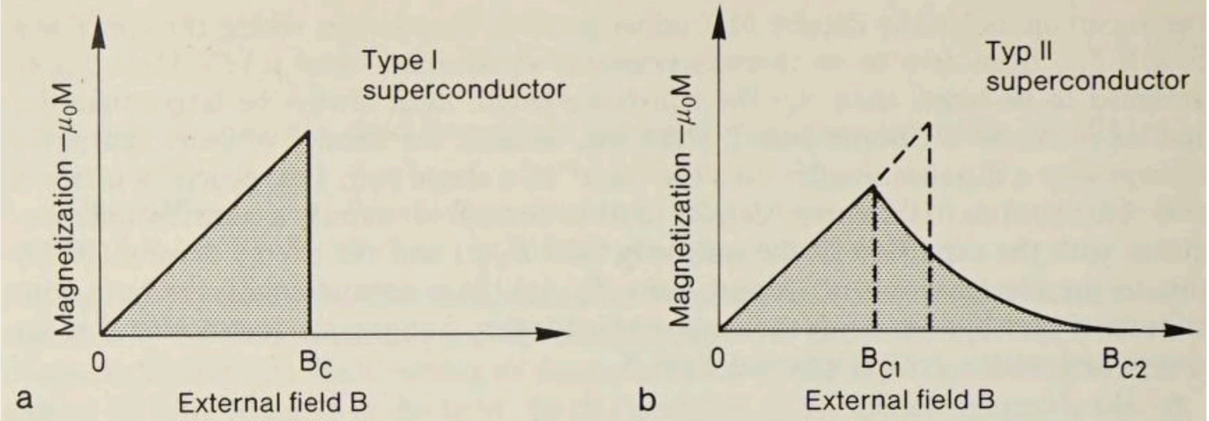


Fig. 10.21. Magnetization curve for a type I superconductor (**a**) and a type II superconductor (**b**). In a type I superconductor there is a single critical field B_c, whereas a type II superconductor has lower and upper critical fields, B_{c1} and B_{c2}

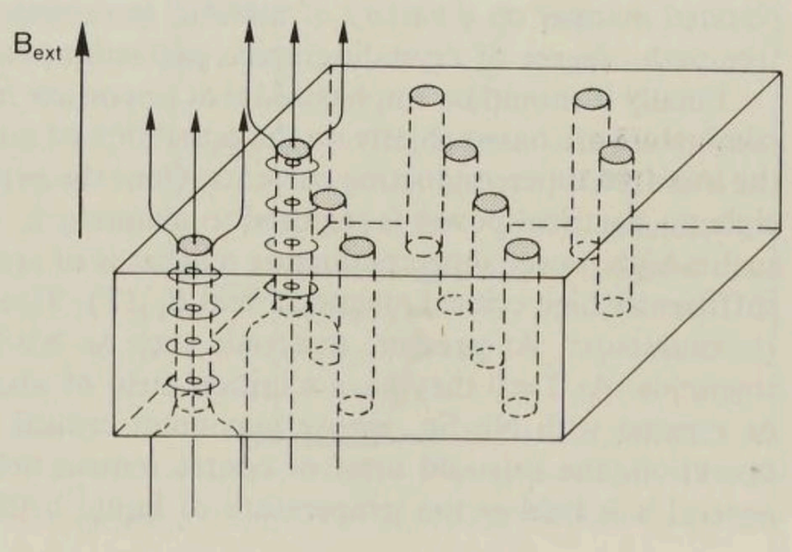
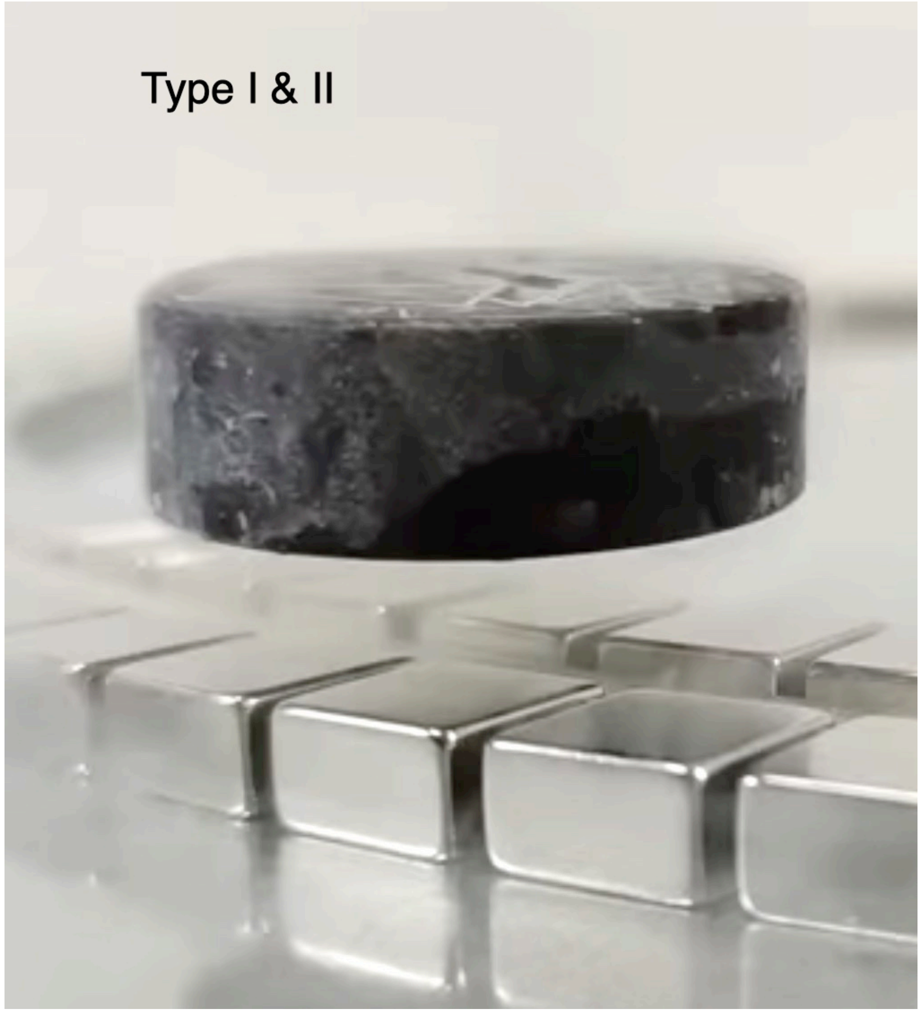


Fig. 10.23. Schematic representation of the Shubnikov phase of a type II superconductor. So-called flux tubes, arranged on a two-dimensional translational lattice, allow the magnetic field to "penetrate". Each flux tube is surrounded by superconducting ring currents and encloses one magnetic flux quantum

[From: Ibach, Lüth, *Solid-state physics*, Springer-Verlag, NY 1991]

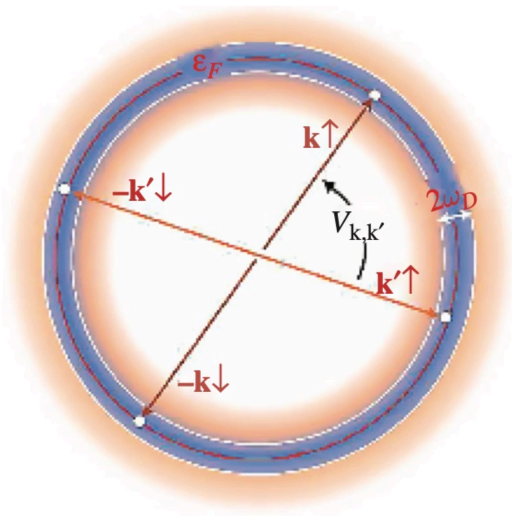
Type I– vs type II– (*aka* high-T_c) superconductor



[From: www.magneticgames.eu/; ⇒ https://tinyurl.com/mputcf5t ⇐]

The BCS theory

Electron-lattice coupling generates weak, attractive interaction between electrons with opposite momenta, provided they're close to the Fermi surface.

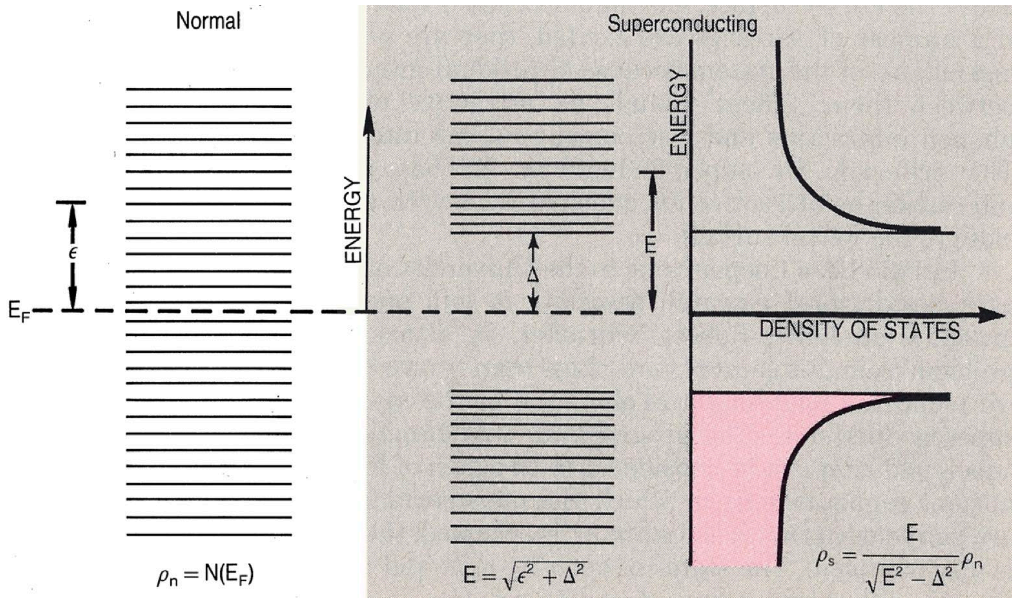


$$V_{\mathrm{k},\mathrm{k}'} = \begin{cases} -g_0/V, & |\epsilon_{\mathrm{k}}| < \omega_D \\ 0, & \text{otherwise} \end{cases}$$

At low temperatures ($T < T_c$) the gap (2Δ) opens in the excitation spectrum.

For $T \to 0$, we have

$$\Delta_0 = 1.764\, k_B T_c.$$



[Bardeen, *Physics Today 43, 25 (1990)*]

Flux quantization

Macroscopic wavefunction for s.c.

$$\Psi = \sqrt{\rho(\mathbf{r})}e^{i\theta(\mathbf{r})};$$

the current density:

$$\mathbf{J} = \frac{\hbar}{m_\star}\left(\nabla\theta - \frac{q_\star}{\hbar}\mathbf{A}\right)\rho.$$

Inside s.c. $\mathbf{J} = 0$, so

$$\hbar\nabla\theta = q_\star\mathbf{A}.$$

[Note: $\mathbf{B} = \mathrm{rot}\,\mathbf{A}$]

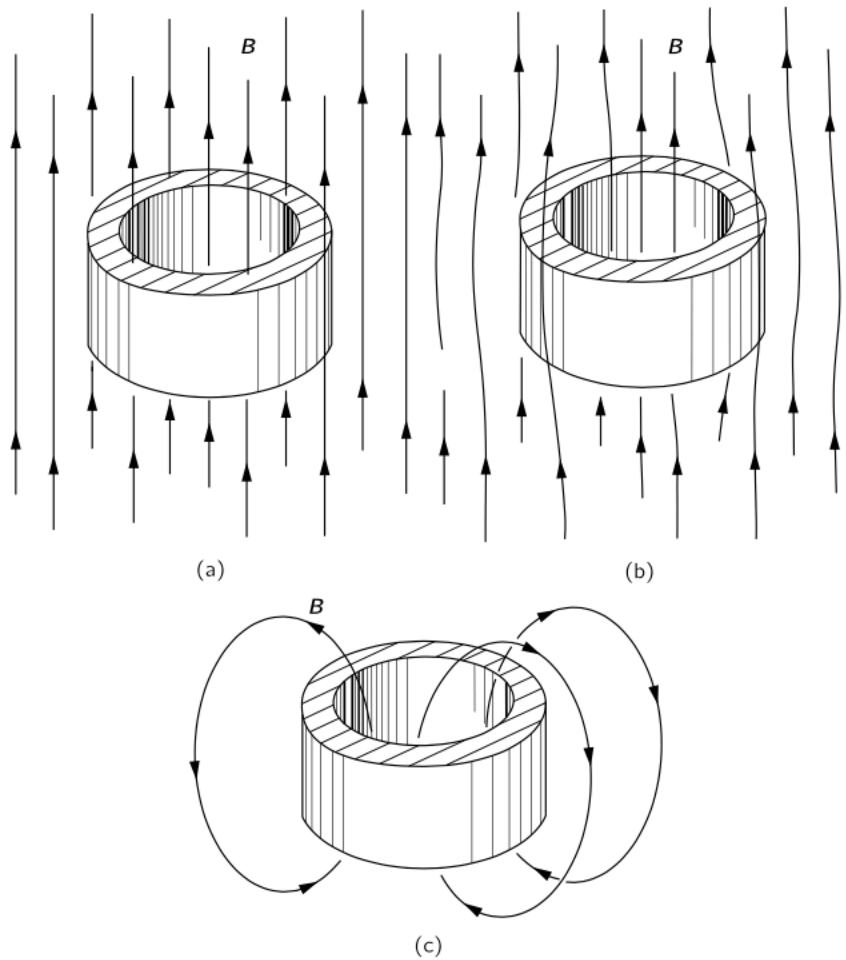


Fig. 21–4. A ring in a magnetic field: (a) in the normal state; (b) in the superconducting state; (c) after the external field is removed.

[From: feynmanlectures.caltech.edu]

Flux quantization

Since $\oint \nabla\theta \cdot d\mathbf{l} = 2\pi n$ (with n–integer), $\oint \mathbf{A} \cdot d\mathbf{l} = \iint \mathbf{B} \cdot d\hat{s} = \Phi$,

we finally get: $\Phi = n\dfrac{h}{q_\star} = n\Phi_0$.

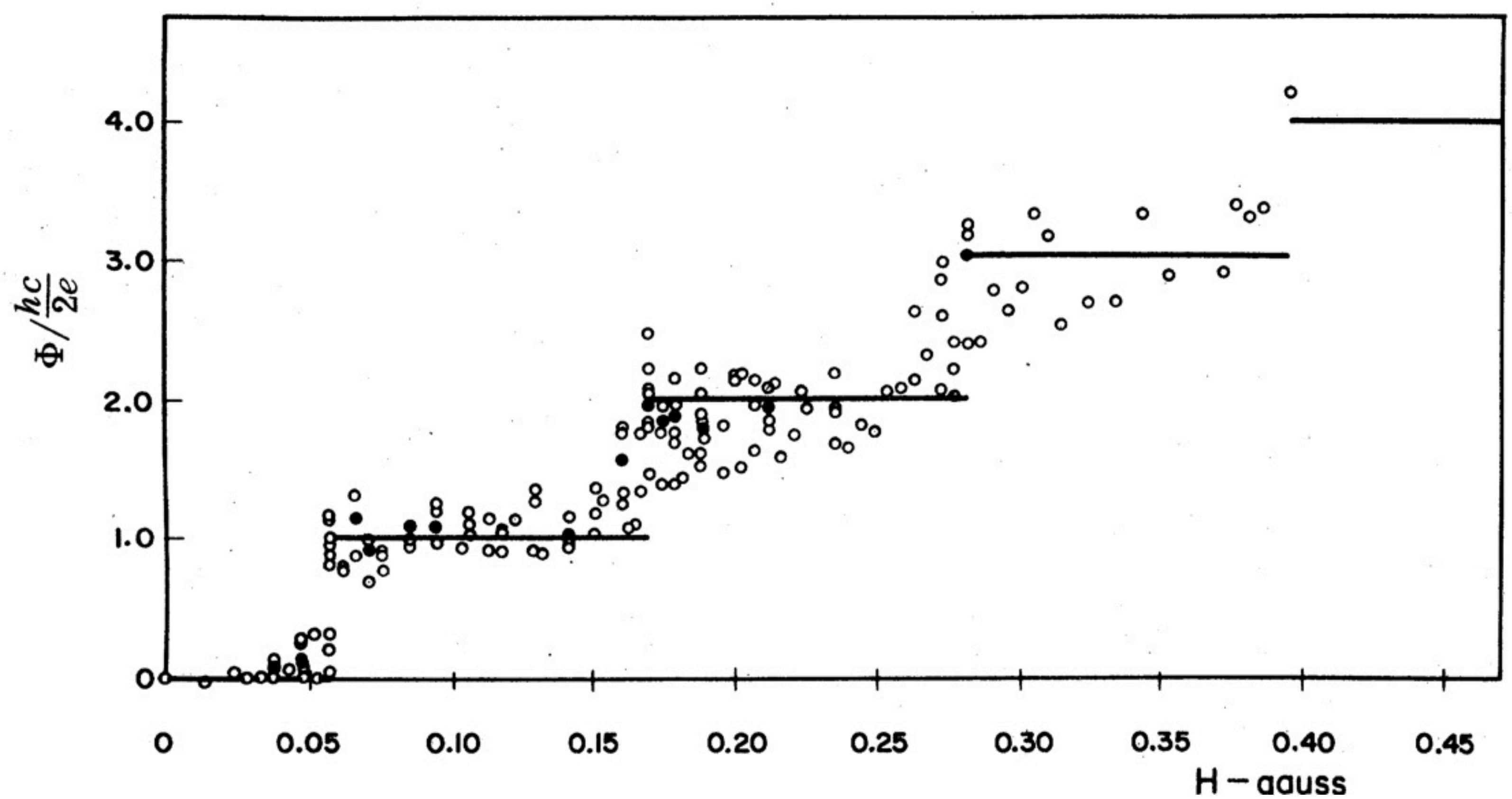
Deaver & Fairbank proven in 1961 that $q_\star = 2e$ ($\Leftrightarrow \Phi_0 = h/2e = 2.0679 \times 10^{-15}$ T m^2) in accordance with the BCS theory. For a ring with a diameter of 1 cm, Φ_0 correspond to the field strength of about 10^{-6} of the Earth's magnetic field.

[***A ring with 2 Josephson junctions = d.c. SQUID***, *nowadays allowing to measure magnetic fields* $< 10^{-17}$ *T.*]

EXPERIMENTAL EVIDENCE FOR QUANTIZED FLUX IN SUPERCONDUCTING CYLINDERS*

Bascom S. Deaver, Jr., and William M. Fairbank
Department of Physics, Stanford University, Stanford, California

(Received June 16, 1961)

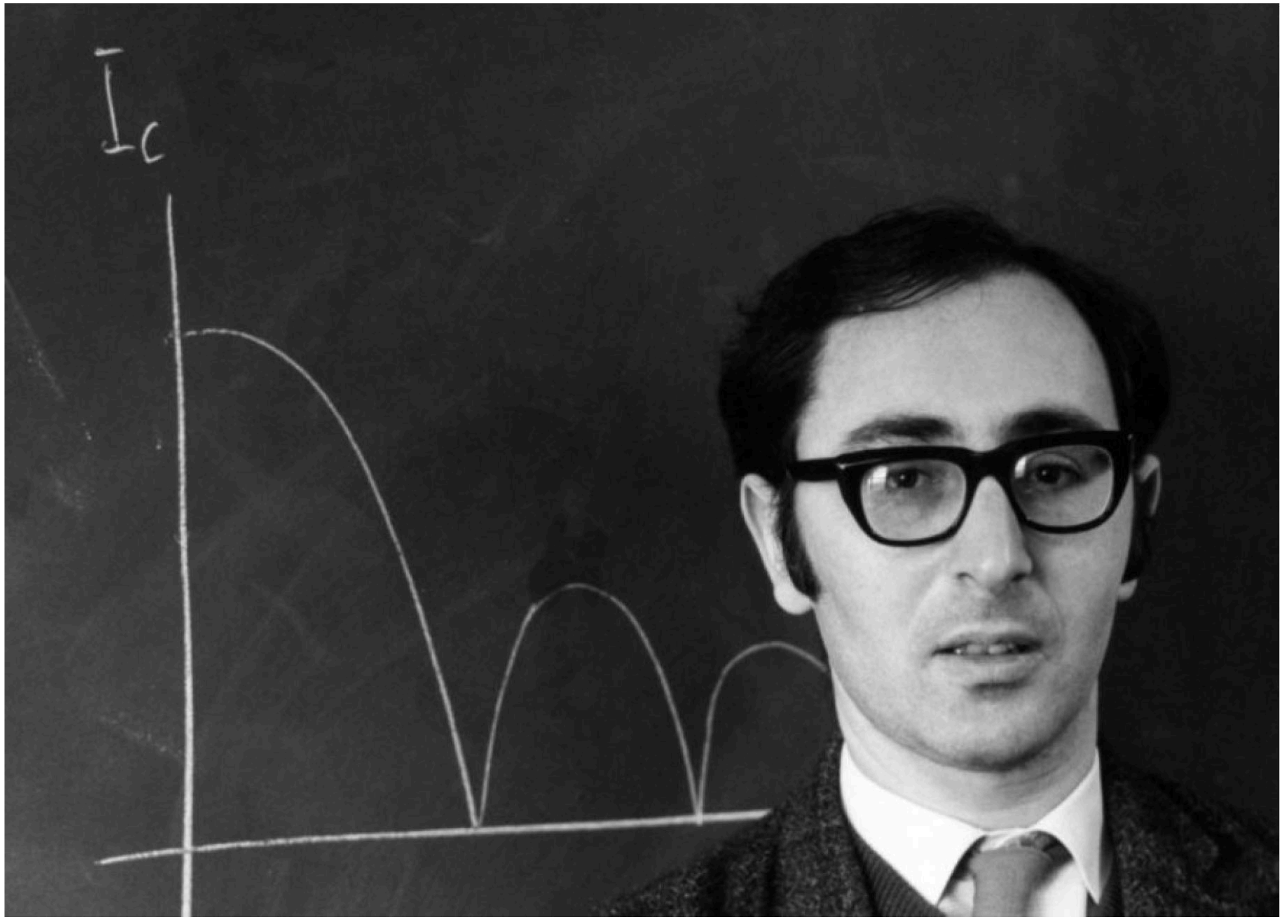


The Josephson effect

— The effect predicted by 22yo student at Cambridge, England.
[*B.D. Josephson, Physics Letters 1, 251 (1962).*]

Sketch on the blackboard show the critical current versus the flux piercing the junction cross-section, i.e.,

$$I_c \propto \frac{\sin \pi\Phi/\Phi_0}{\pi\Phi/\Phi_0}.$$



The Josephson effect

— Experimental confirmation came shortly afterwards.
[*P.W. Anderson, J.M. Rowell, Phys. Rev. Lett.* ***10****, 230 (1963).*]

— Josephson has share 1/2 of The Nobel Prize in Physics 1973, with Leo Esaki (1/4) and Ivar Giaever (1/4), just one year after Nobel Prize for Bardeen, Cooper and Schrieffer for their theory (!)

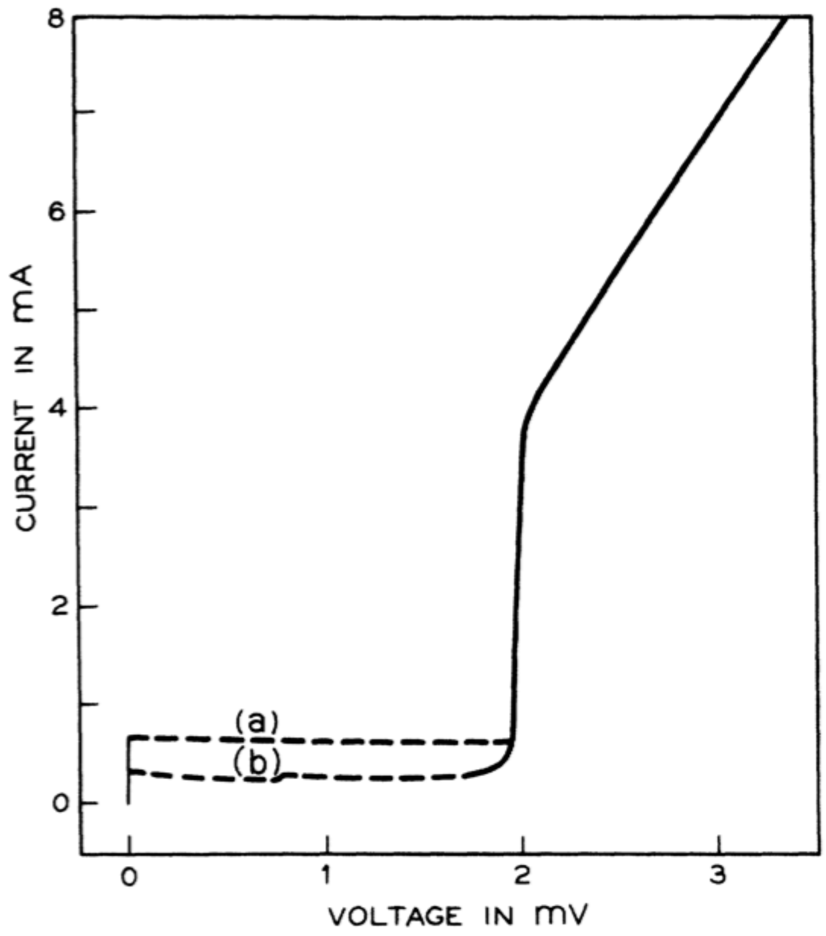


FIG. 1. Current-voltage characteristic for a tin-tin oxide-lead tunnel structure at ~1.5°K, (a) for a field of 6×10^{-3} gauss and (b) for a field 0.4 gauss.

The Josephson effect — *key features*

— The supercurrent may pass thin (~1 nm) insulator layer separating two s.c.-s [no voltage across for $|I| \leqslant I_c$], the phase difference θ between superconductors follows

$$I = I_c \sin\theta, \text{ with the critical current } I_c \approx \frac{\pi\Delta_0}{2eR_N} \quad (T \to 0),$$

where Δ_0 is the superconducting gap and R_N is the resistivity in the normal state. [⇒ *d.c. Josephson effect*]

— When constant voltage (V) is applied, the alternating current appears, with the frequency $\left(2e/\hbar\right) V$. [⇒ *a.c. Josephson effect*]

A simple reasoning build on *Ginzburg-Landau* theory

The current along x-axis: $$J_x = \frac{2e}{2m}\left[\Psi^\star\left(-i\hbar\frac{\partial}{\partial x} - 2eA_x\right)\Psi + \text{c.c.}\right].$$

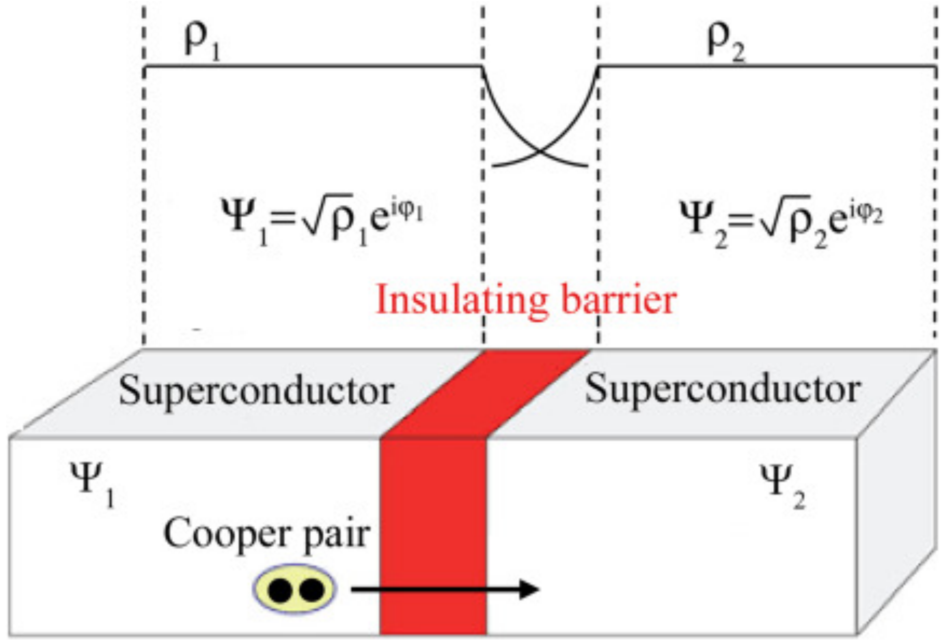
For a thick barrier, we have: $$-i\hbar\frac{\partial\Psi_{1,2}}{\partial x} - 2eA_x\Psi_{1,2} = 0.$$

Otherwise, one can suppose that

$$\left(-i\hbar\frac{\partial}{\partial x} - 2eA_x\right)\Psi_{1,2} = -\frac{i\hbar}{b}\Psi_{2,1}.$$

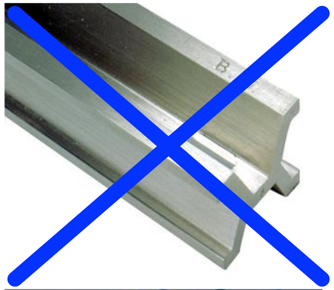
Substituting into the eq. for J_x:

$$\Rightarrow\ J_x = \frac{2e\hbar}{mb}|\Psi_1||\Psi_2|\sin\left(\varphi_2 - \varphi_1\right).$$



[See: *Cyrot, Pavuna, Introduction to Superconductivity and High Tc Materials, World Scientific, Singapore, 1992*; *figure from*: sciencedirect.com]

The quantum metrological triangle



Efekt Josephsona:

$$I \propto \sin\left(\frac{4\pi eV}{h}\right) t$$

$$\Rightarrow \; f_J = 2eV/h,$$

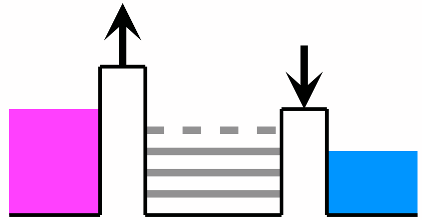
$$K_J = 2e/h = \\ = 483597.853(3)\,\mathrm{GHz/V}$$

The NIST Reference on Constants, Units, and Uncertainty

f [Hz]

Pompa kwantowa (?)

$I = const \times e\, f$



(m, kg, s) $\Updownarrow$ (V, A, Hz)

U [V]

I [A]

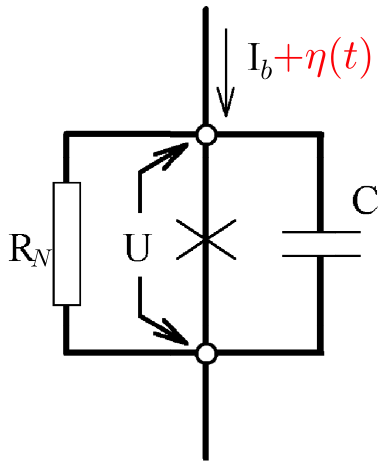
QHE: $R_H = h/(\nu e^2), \;\; \nu = 1, 2, \ldots$

$R_K = h/e^2 = 25812.807456(6)\,\Omega$

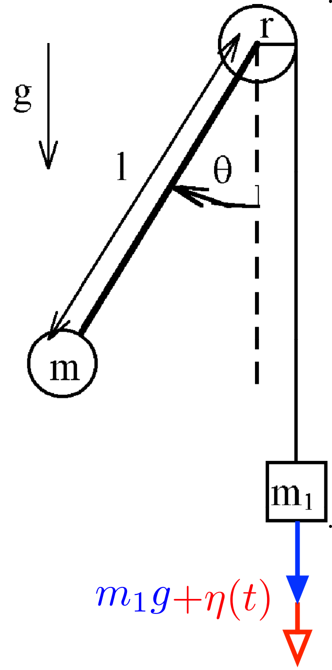
The RCSJ model

The total current:

$$C\dot{U} + \frac{U}{R_N} + I_c \sin\theta - I_b = \eta(t).$$



$\Longrightarrow$



Since $U = \dfrac{\hbar}{2e}\dot{\theta} = \dfrac{\Phi_0}{2\pi}\dot{\theta}$, and

$\dot{U} = \dfrac{\Phi_0}{2\pi}\ddot{\theta}$, one can rewrite

$$C\frac{\Phi_0}{2\pi}\ddot{\theta} + R_N^{-1}\frac{\Phi_0}{2\pi}\dot{\theta} + I_c \sin\theta - I_b = \eta(t),$$

being equivalent to the ***equation of motion for a pendulum***, subjected to a constant torque ($\propto I_b$) and a perturbation ($\propto \eta(t)$) [*thermal AND/OR harmonic*].

The RCSJ model

The total energy:

$$H = E_{\rm kin} + E_{\rm pot},$$

$$E_{\rm kin} = \frac{Q^2}{2C}, \quad (\, Q = CU \,)$$

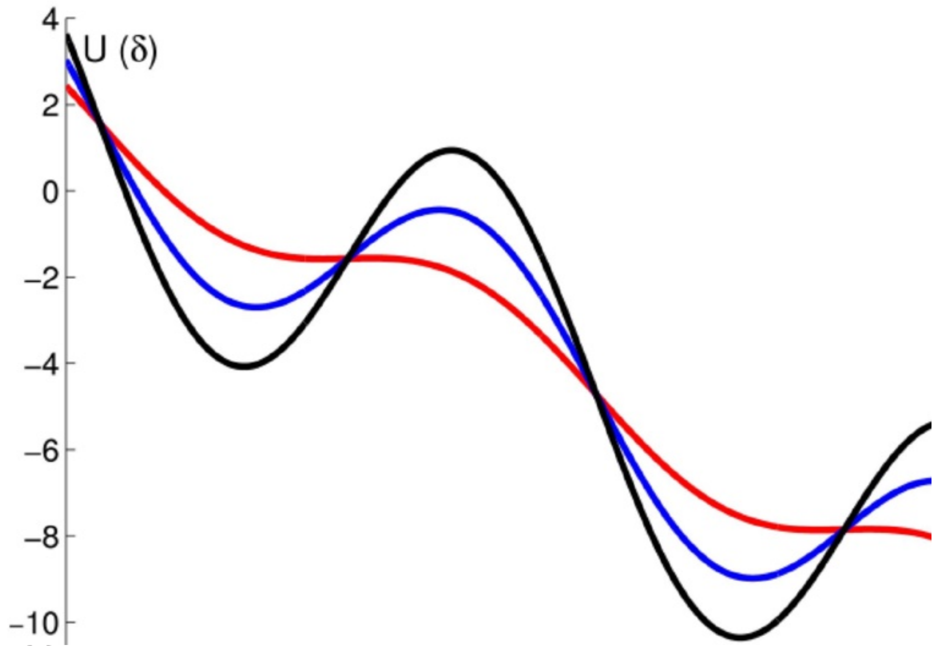
$$E_{\rm pot} = -\, I_b \frac{\Phi_0}{2\pi}\, \theta - E_J \cos\theta,$$

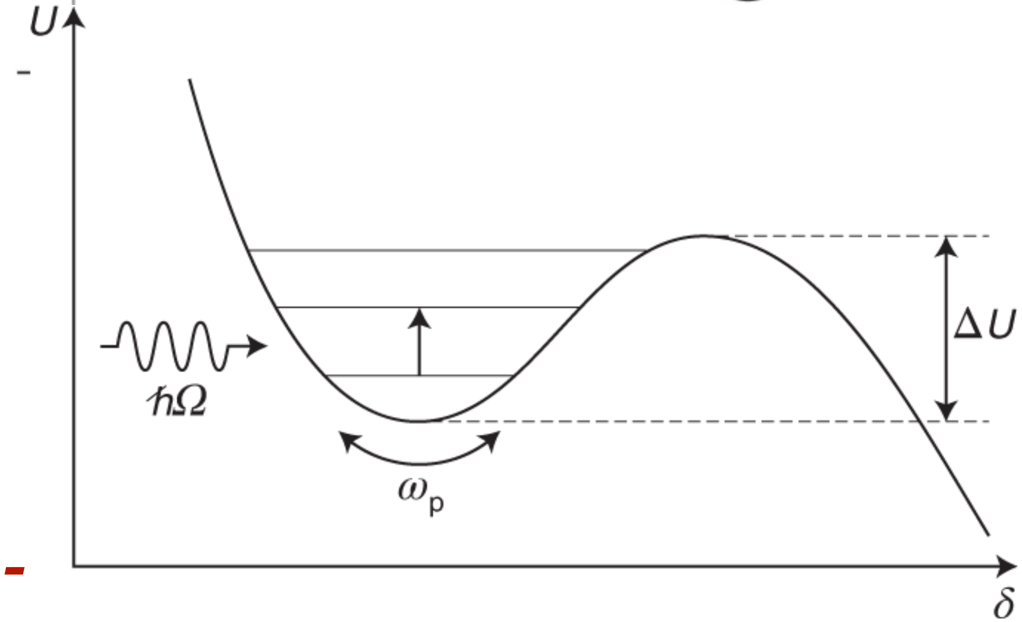
where $E_J = I_c \Phi_0 / 2\pi$.

(⇒*Tilted washboard potential*)

Next step: $\quad [\hat{Q}, \hat{\theta}] \propto -\, 2e\, i,$

$\Delta Q \delta\theta \geq e$ (⇒ ***quantum-mechanical operators,*** *uncertainty principe, etc.*)





Footnote: The above is no a guess but follows from the BSC theory. Up to the normalization, the BCS wavefunction can be written as $|BSC\rangle = \prod_k \left(1 + \phi_k c^\dagger_{k\uparrow} c_{-k\downarrow}\right)|0\rangle = \sum_n \frac{1}{\sqrt{n!}}|n\rangle$,

where $|n\rangle = \frac{1}{\sqrt{n!}}(\Lambda^\dagger)^n|0\rangle$, with $\Lambda^\dagger = \sum_k \phi_k c^\dagger_{k\uparrow} c_{-k\downarrow}$, is a state

containing n pairs. The gauge transformation $|BSC\rangle \rightarrow |\alpha\rangle$, defined via the substitution $c^\dagger_{k\sigma} \rightarrow e^{i\alpha} c^\dagger_{k\sigma}$, immediately leads to the number operator $\hat{N}|\alpha\rangle = \sum_n \frac{1}{\sqrt{n!}} 2ne^{2in\alpha}|n\rangle = -i\frac{d}{d\alpha}|\alpha\rangle$, and

to $[\alpha, N] = i$.

The Noble-prize papers

[0]

VOLUME 53, NUMBER 13 PHYSICAL REVIEW LETTERS 24 SEPTEMBER 1984

Resonant Activation from the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, Daniel Esteve,[a] and John Clarke
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(Received 26 July 1984)

[1]

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)

[2]

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)

[1] Martinis et al., *PRL 1985*

The escape time (τ_{esc}) is the average time, after which voltage appers

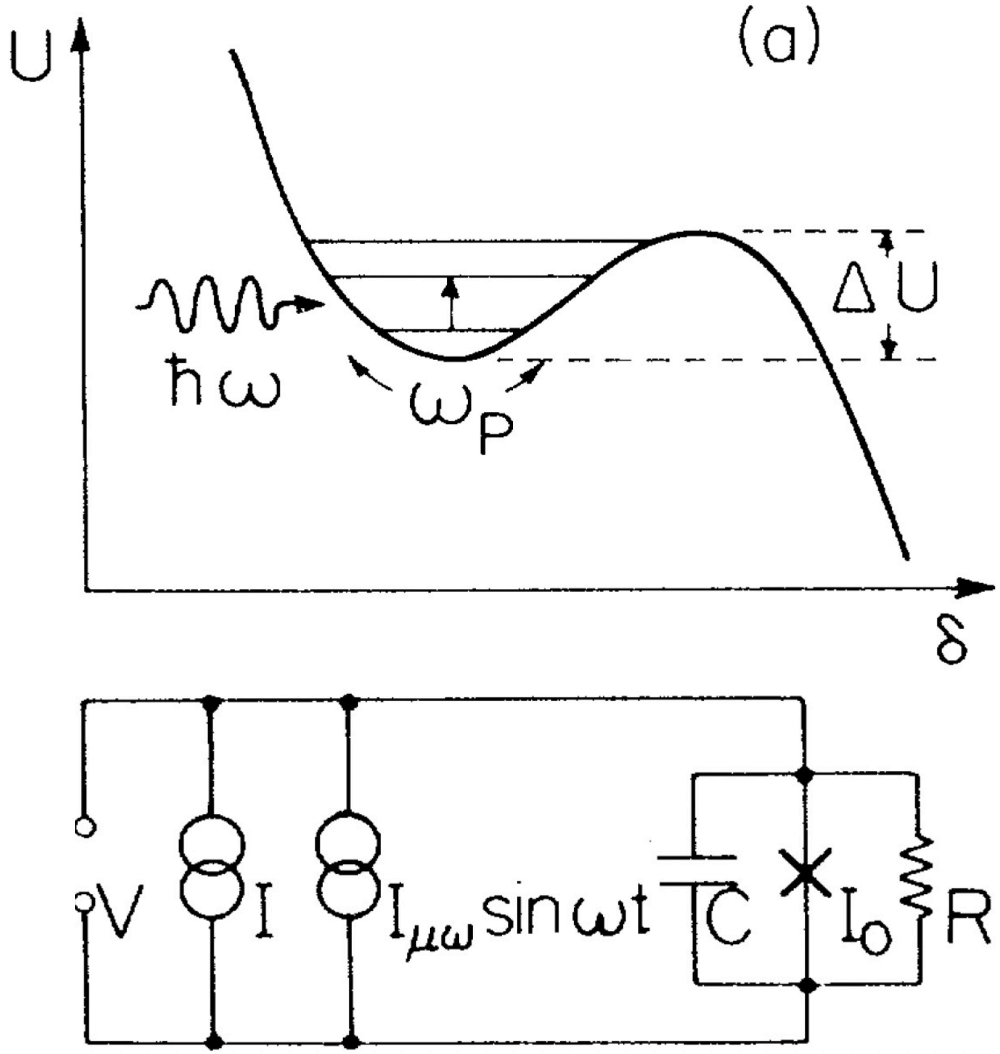
— A cubic potential is a sufficient approx. of the washboard potential

— Thermal escape rate ($k_B T \gg \hbar\omega_p$):

$$\Gamma_t = \tau_{\text{esc}}^{-1} = a_t(\omega_p/2\pi)\exp(-\Delta U/k_B T),$$

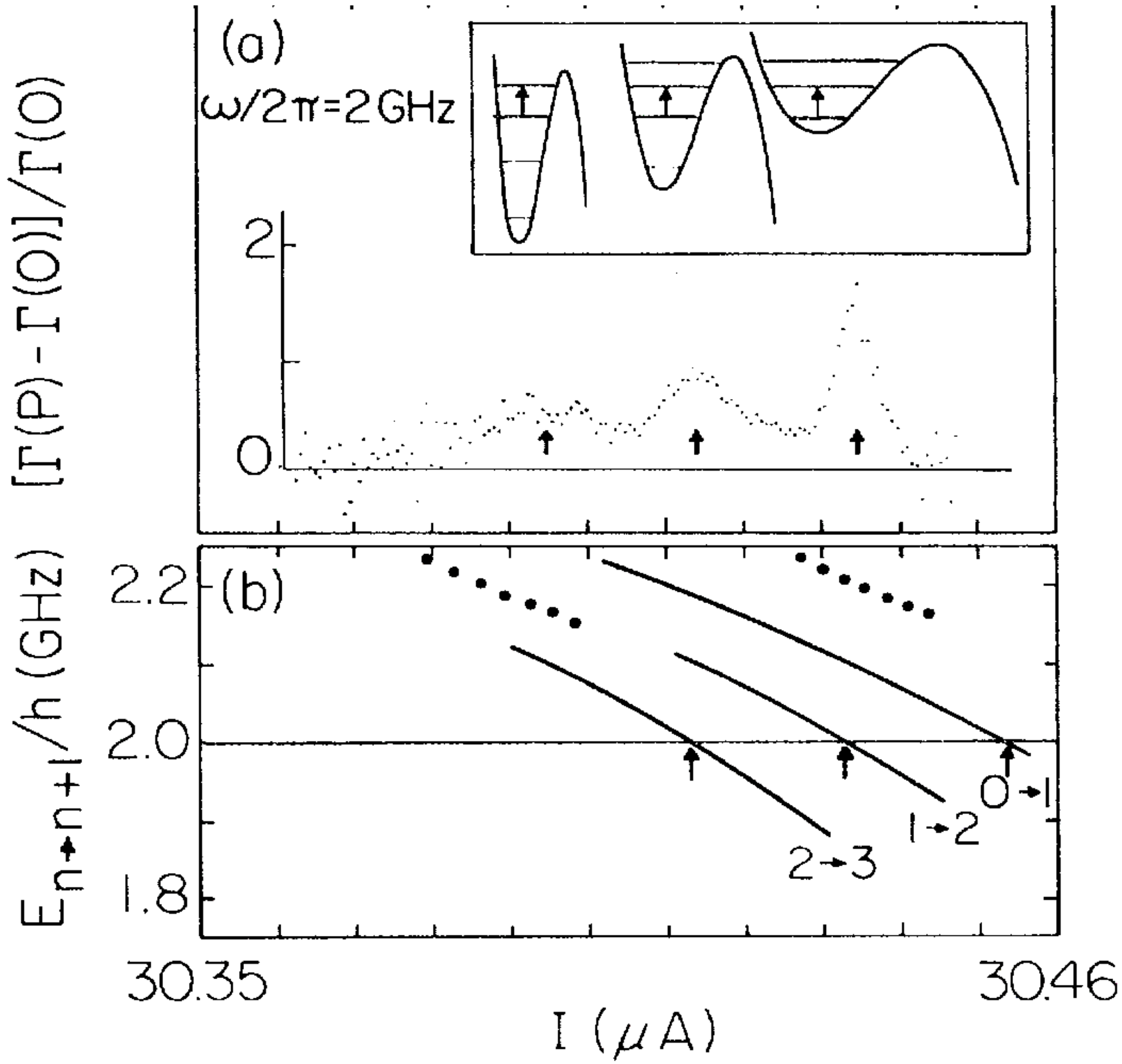
where

$$a_t = 4/[\sqrt{1 + Qk_B T/1.8\Delta U} + 1]^2,$$
$Q = \omega_p RC$, and
$$\omega_p = (2\pi I_c/C\Phi_0)^{1/2}[1 - (I/I_c)^2]^{1/4}.$$



[1] Martinis *et al.*, *PRL '85*

The ratio $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$, with the microwave power P on/off, displayed as a function of a bias current for a fixed frequency, shows resonances corresponding to transitions between subsequent quantum levels [*which are NOT equally–spaced due to anharmonicity!*].



***Is it really a quantum phenomenon** or just perturbation-assisted thermal escape near the resonance ?!*

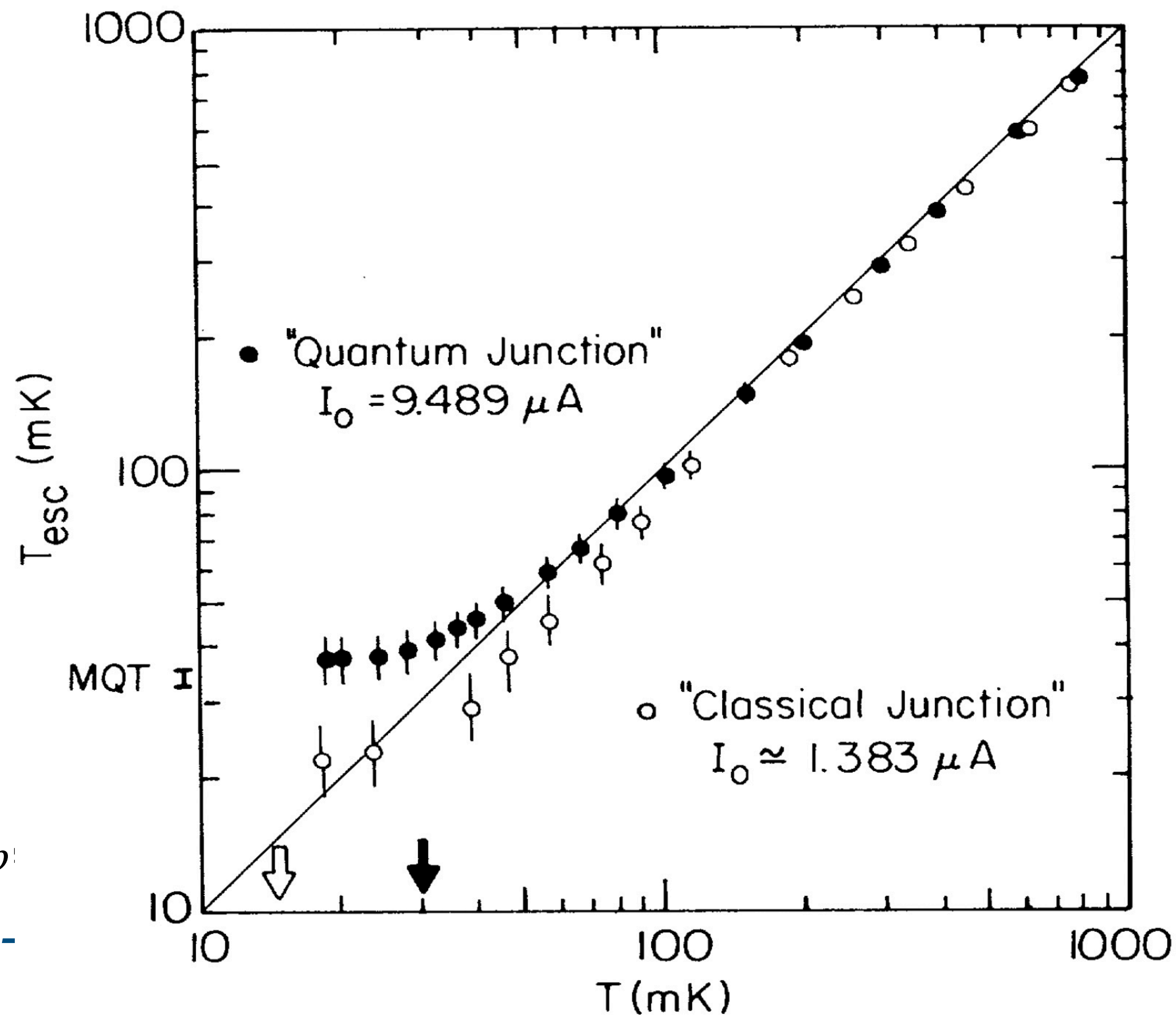
[2] Devoret *et al.*, *PRL 1985*

Let's define the effective "escape temperature" via

$\Gamma = (\omega_p/2\pi)\exp(-\Delta U/k_B T_{\rm esc})$.

As long as $T_{\rm esc} \approx T$ (the actual temperature), the behavior is *classical*.

However, at low temperatures, and high I_c, such that $k_B T \ll \hbar\omega_p$, $T_{\rm esc}$ saturates [*i.e., becomes temperature–independent*].



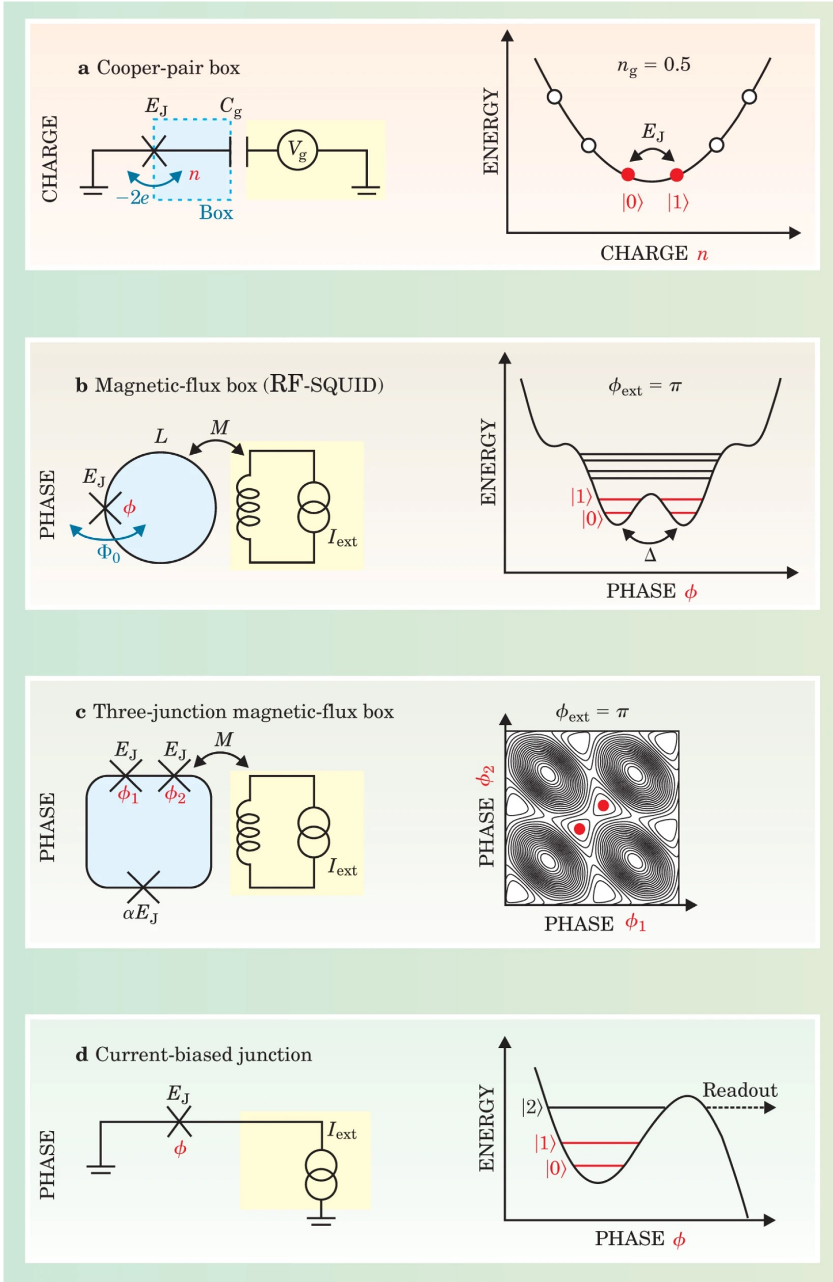
⇒ ***The "quantum junction" was build!***

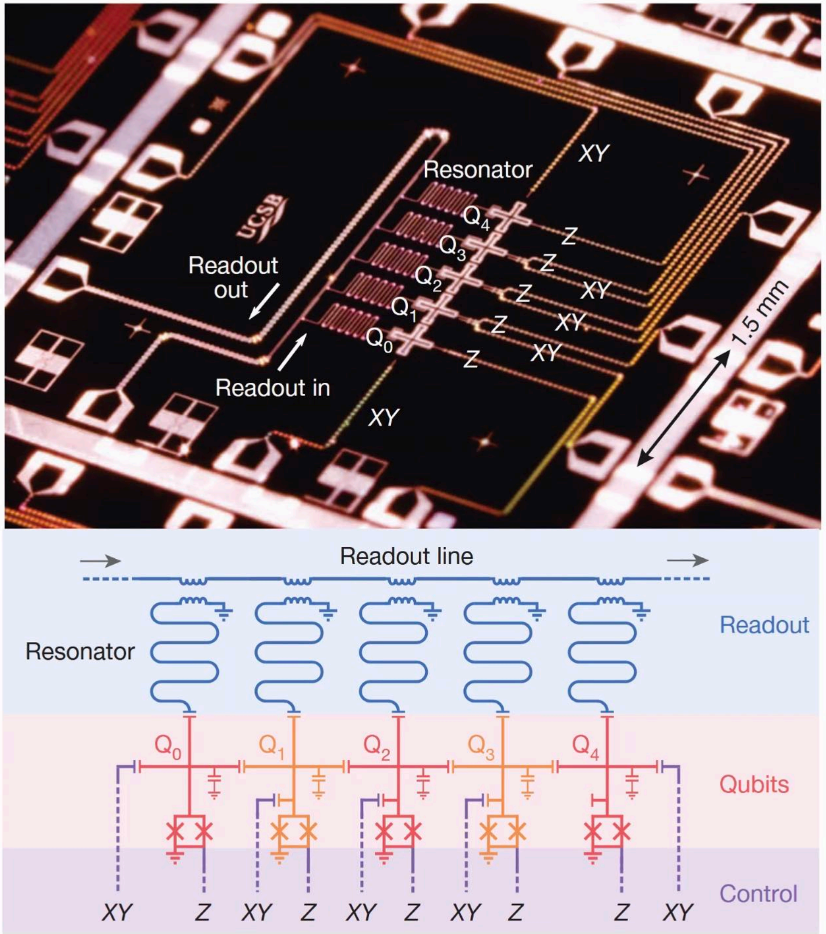
Consequences

The experimental setup by Clarke, Devoret, and Martinis, properly improved, constitutes a platform for several types of ***superconducting qubits***.

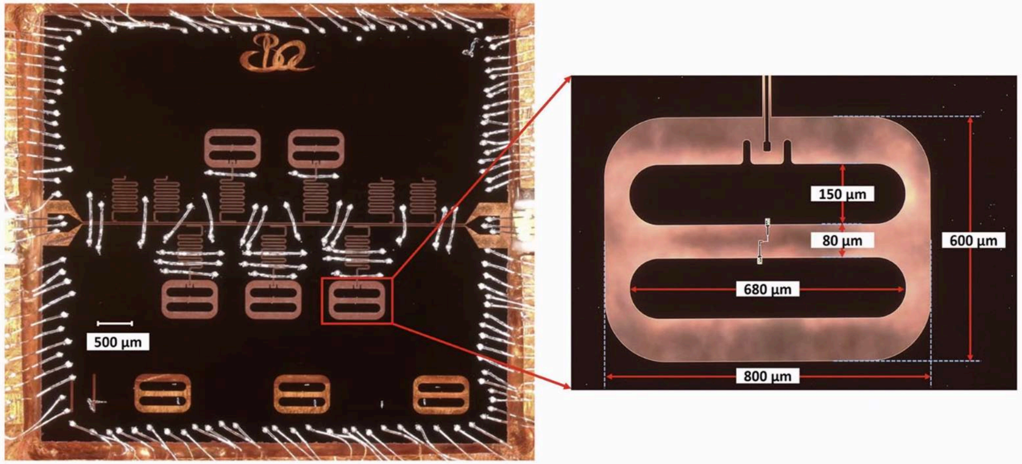
Josephson-based technology seems close to become practical (?) [*fault tolerance, quantum advantage...*]

[*You & Nori, Phys. Today 58, 42 (2005)*]





[R. Barends et al. Nature, 2014, 508(7497), 500]



[C. Wang et al. Npj Quantum Information, 8(1), 3, 2022]

Michael H. Devoret (b. 1953)

PhD in 1982, Paris Saclay (atomic optics). Postdoc at UC Berkeley, then Saclay, then Yale University.

Since 2023 — *Google Quantum AI* (hardware scientist) & professor at Santa Barbara.

Research: 1990s— quantum sensors, quantum dots, single-electron transistor.

Letter | Published: 03 April 1997

Individual single-wall carbon nanotubes as quantum wires

Sander J. Tans, Michel H. Devoret, Hongjie Dai, Andreas Thess, Richard E. Smalley, L. J. Geerligs & Cees Dekker

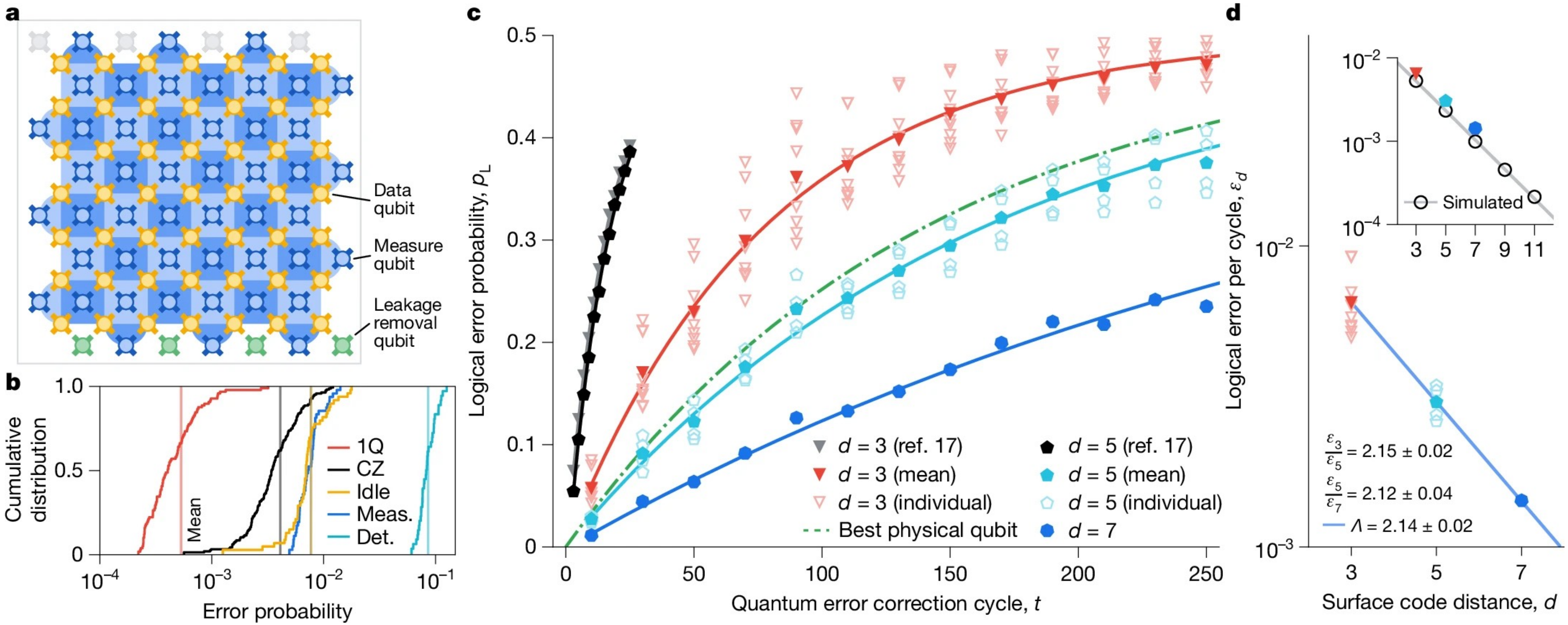
Nature **386**, 474–477 (1997) | Cite this article

Michael H. Devoret — *research*

2010: “*Introduction to Quantum Noise, Measurement and Amplification*” [Reviews of Modern Physics **82**, 1155 (2010).]

2016+: Several results on **quantum error corrections**
[*Ofek et al., Nature **536**, 441 (2016); Sivak et al., Nature **616**, 50 (2023).*]

2025: *Google Quantum AI* paper on ***the Willow chip***: “*Quantum error correction below the surface code threshold*”
[*Nature **638**, 920–926 (2025)*]



[From: *Nature* ***638***, *920–926 (2025)*]

John M. Martinis (b. 1958)

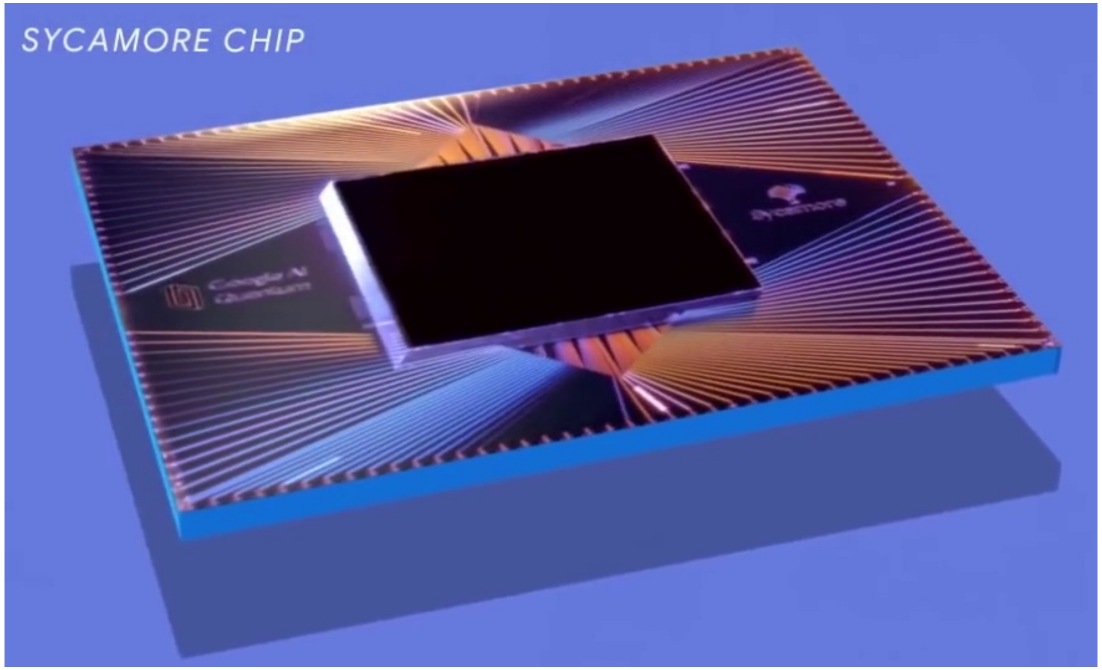
— PhD 1987, UC Berkeley (*with John Clarke*)

— 1990s: quantum sensors

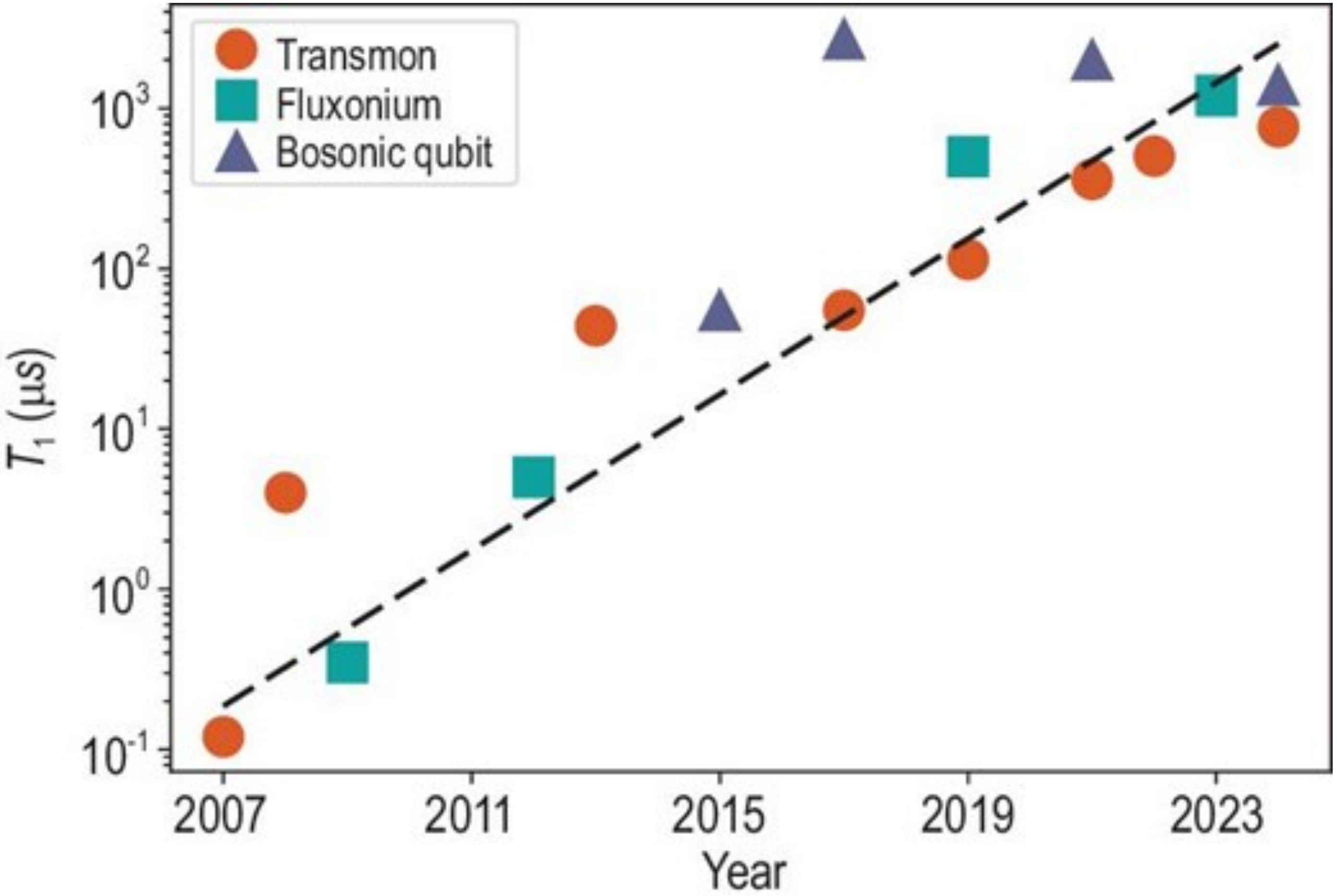
— 2000s: qubits, decoherence, quantum computing
[See: *"Violation of Bell's inequality in Josephson phase qubits"*, Nature **461**, 504 (2009)]

— Since 2014: lead *Google Quantum AI Lab*.

— The **Sycamore chip**:
"Quantum supremacy using a programmable superconducting procesor"
[Nature **574**, 505 (2019).]

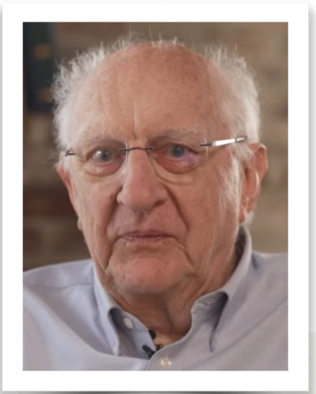


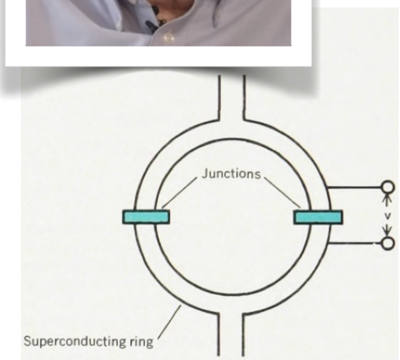
Progress in quantum coherence

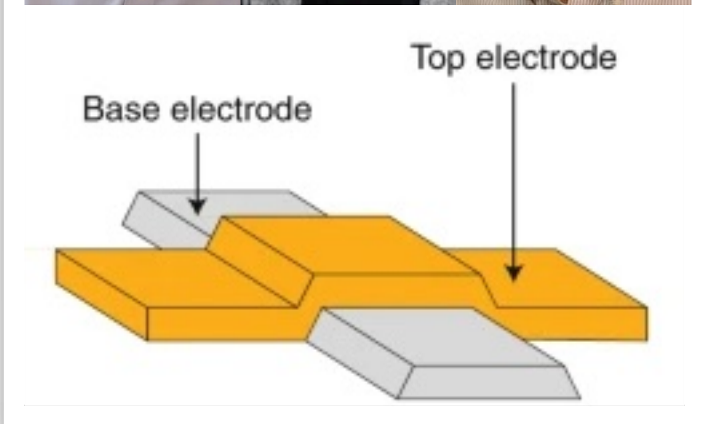


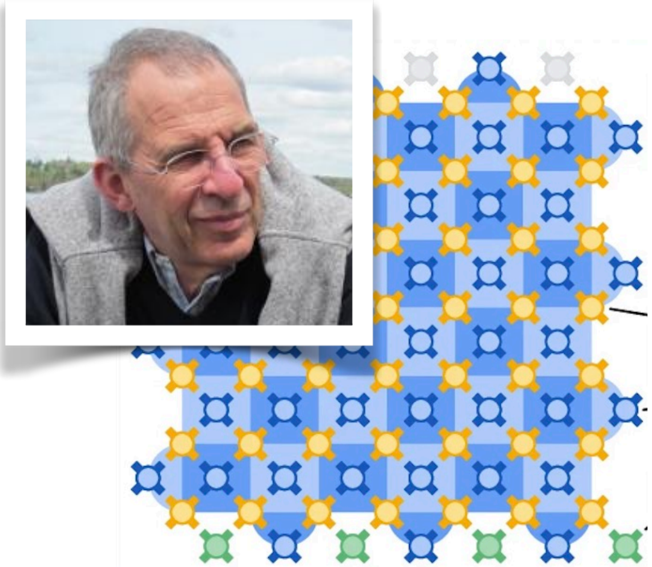
[Yao-Yao Jiang *et al.*, *“Advancements in superconducting quantum computing”, Nat. Sci. Rev. 12, nfaw246 (2025)*]

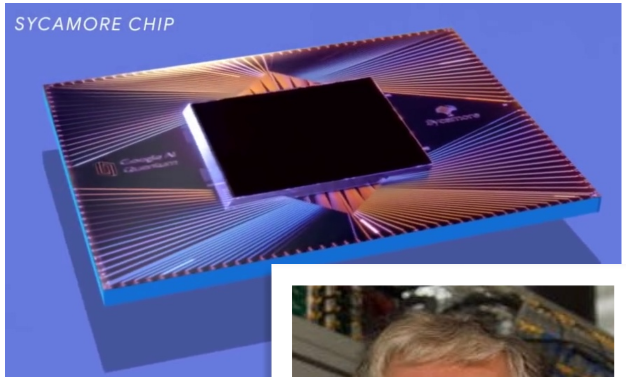
Overview

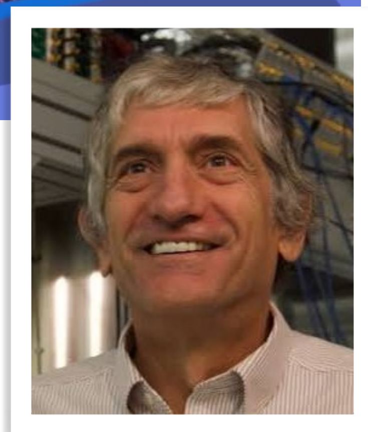



Junctions
Superconducting ring


Top electrode
Base electrode




SYCAMORE CHIP



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