Superconductivity - Overview

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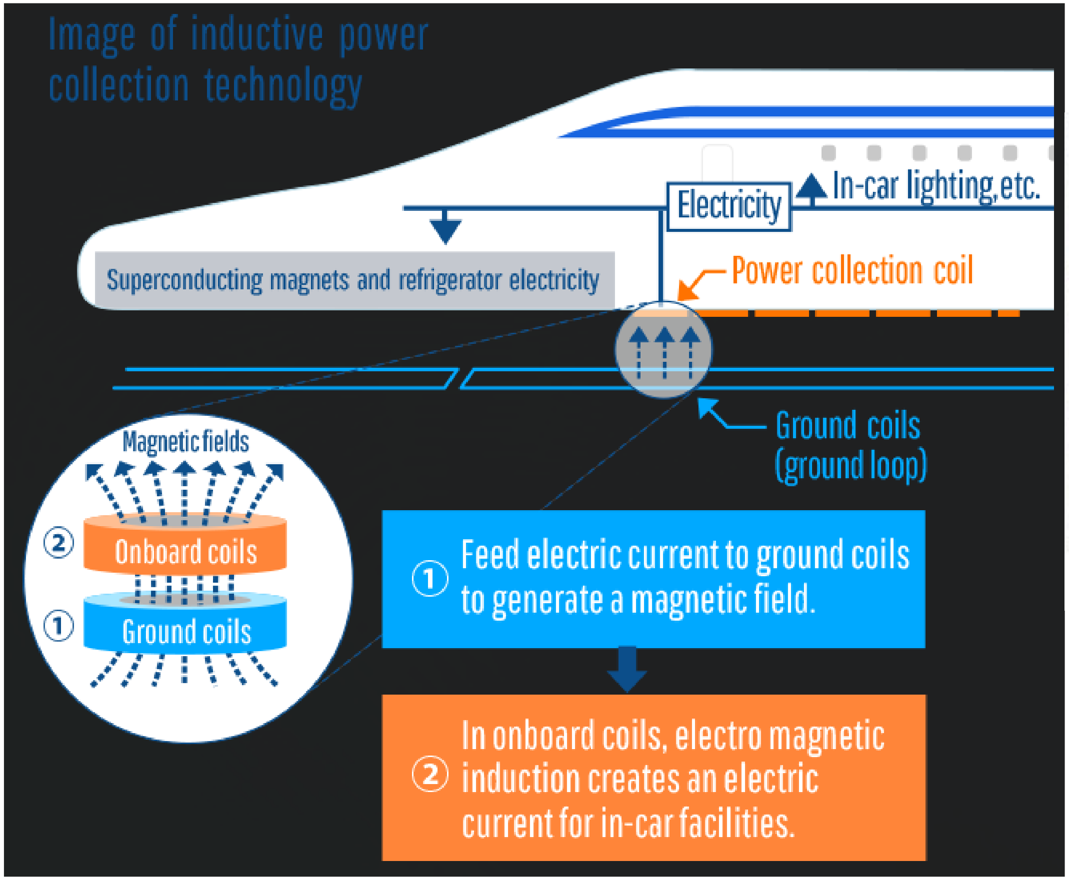
Importance of superconductivity: Qubits and modern quantum computers are made of superconductors

Superconducting-magnet levitation train



The L0 Series, a prototype vehicle based on SCMaglev technology, holds the record for fastest crewed rail vehicle with a record speed of 603 km/h (375 mph).
Time Urbana-Chicago: only ~25 min

The SCMaglev system uses an electrodynamic suspension (EDS) system. The train's bogies have superconducting magnets installed, and the guideways contain two sets of metal coils.

Superconducting magnets for MRI

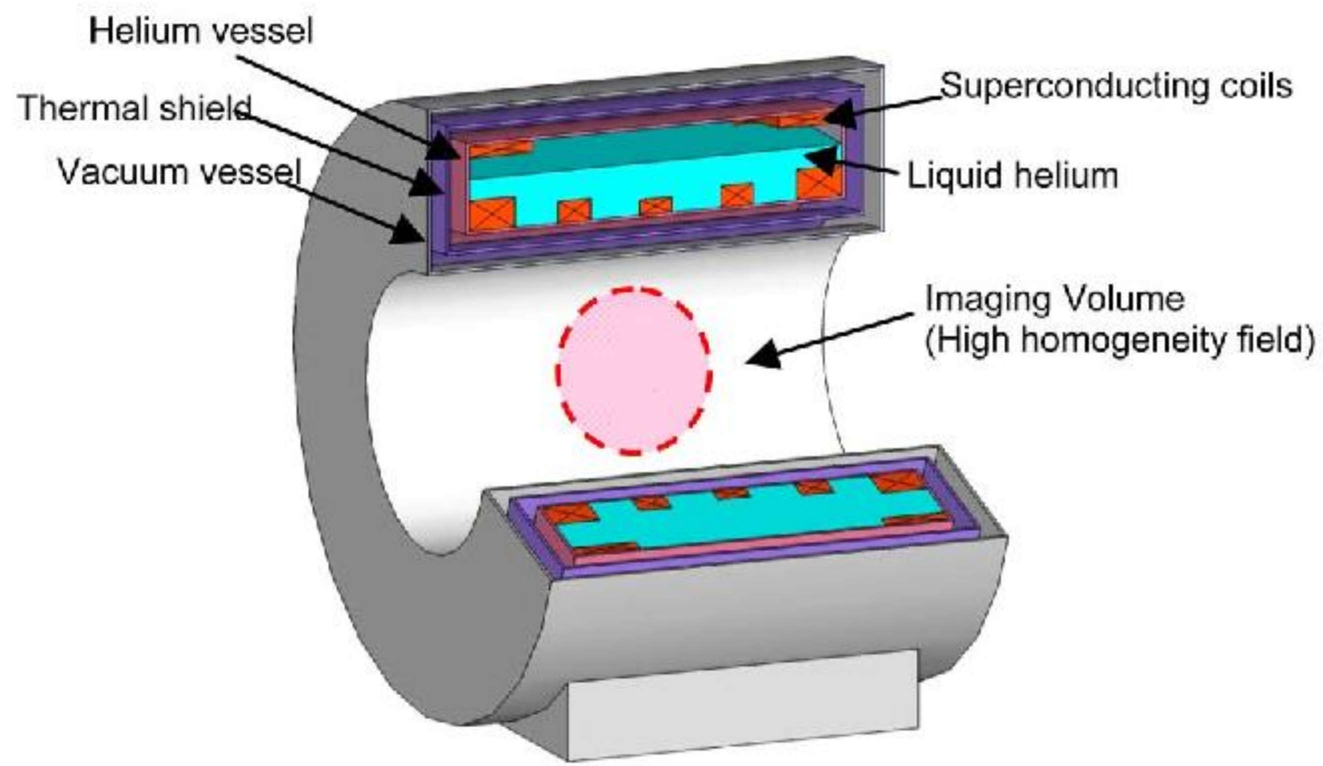


Fig. 2. Cross-sectional view of the magnet.

Published in IEEE transactions on applied superconductivity 2014

Super-Stable Superconducting MRI Magnet Operating for 25 Years

Shunji Yamamoto | Katsumi Konii | H. Tanabe | S. Yokoyama | T. Matsuda | T. Yamada

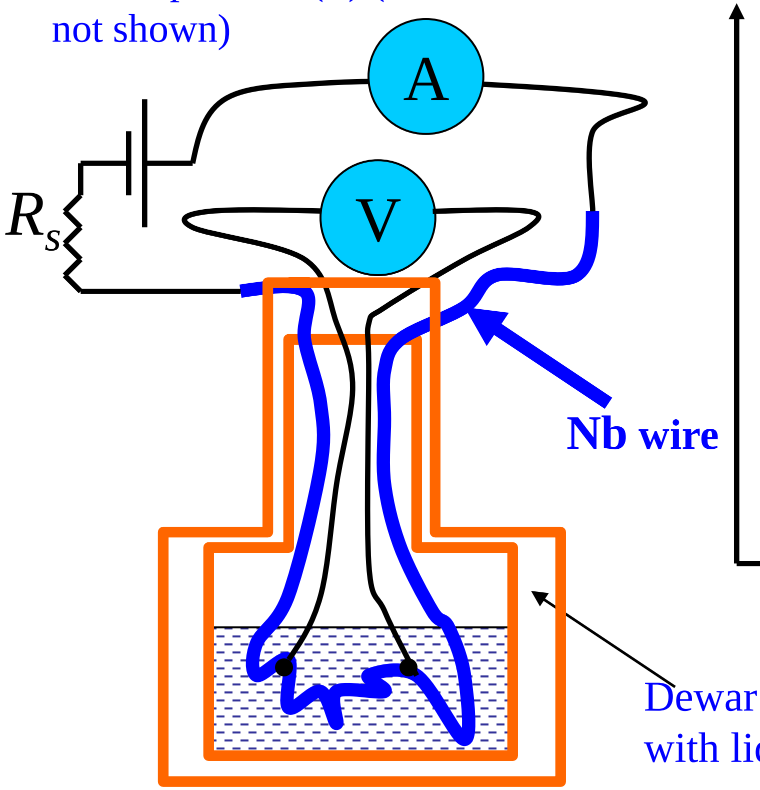
How to measure superconducting transitions

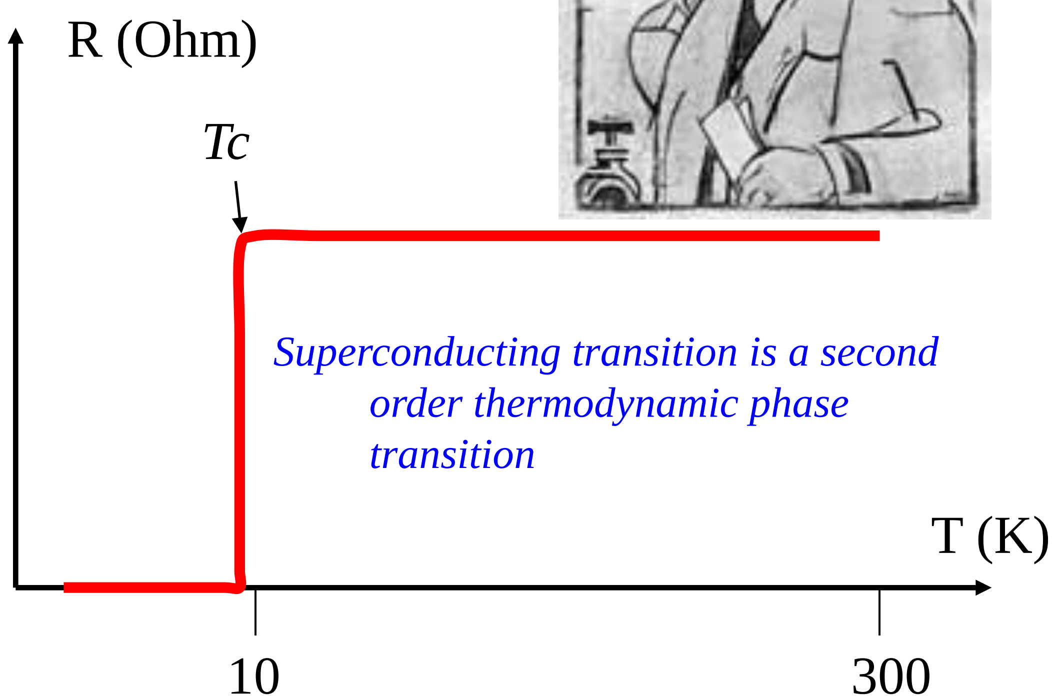
Electrical resistance of some metals drops to zero below a certain temperature which is called "critical temperature“ (H. K. O. 1911)

How to observe superconductivity

1. Take Nb (niobium) wire
2. Connect to a voltmeter and a current source
3. Immerse into helium Dewar (T=4.2 K boiling point)
4. Measure electrical resistance (R) versus the temperature (T) (thermometer is not shown)

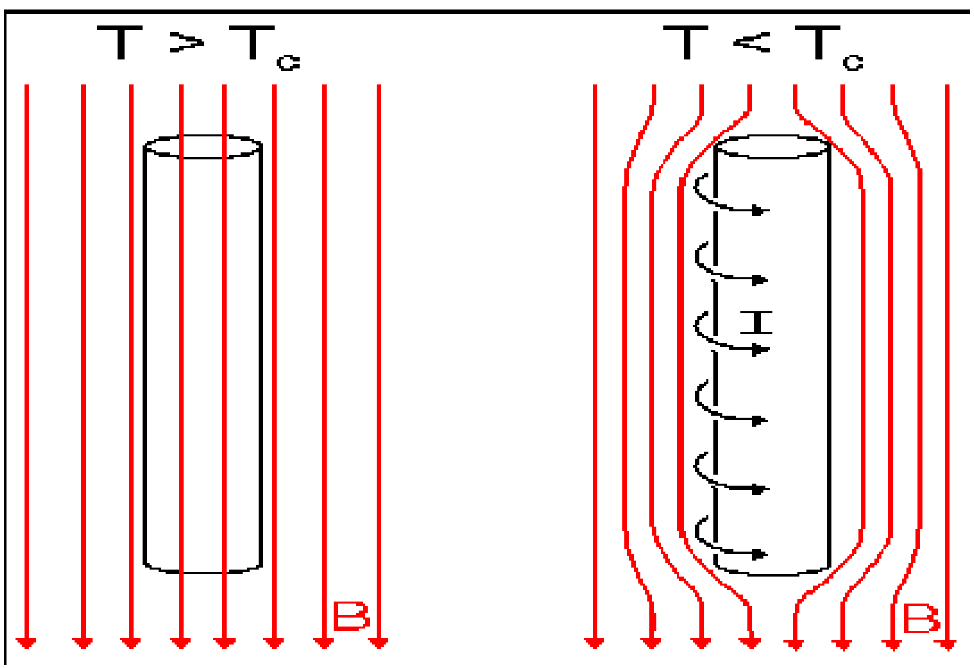
Heike Kamerling Onnes





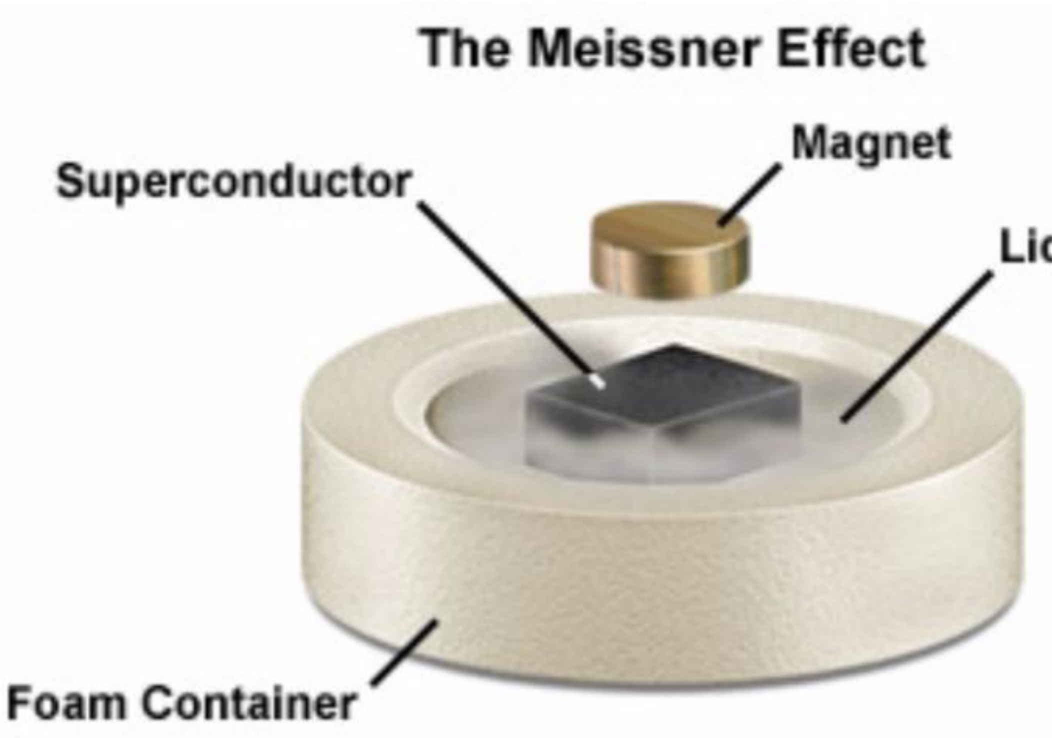
Meissner effect – the key signature of superconductivity

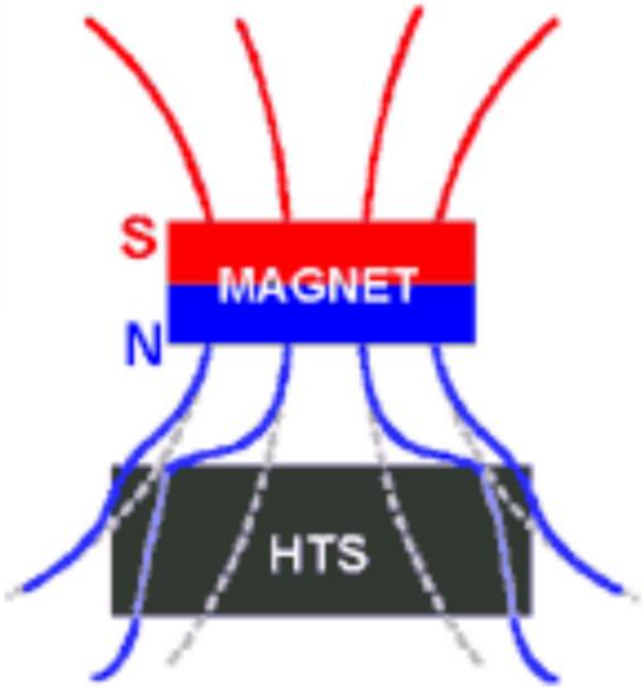
Formula	T_C (K)	H_C (T)	Type	BCS
Elements				
Al	1.20	0.01	I	yes
Cd	0.52	0.0028	I	yes
Diamond:B	11.4	4	II	yes
Ga	1.083	0.0058	I	yes
Hf	0.165		I	yes
α-Hg	4.15	0.04	I	yes
β-Hg	3.95	0.04	I	yes
In	3.4	0.03	I	yes
Ir	0.14	0.0016[7]	I	yes
α-La	4.9		I	yes
β-La	6.3		I	yes
Mo	0.92	0.0096	I	yes
Nb	9.26	0.82	II	yes
Os	0.65	0.007	I	yes



Theory of superconductivity:
"BCS" – due to Bardeen, Cooper and Schrieffer

Interesting phenomenon: Magnetic levitation





Levitation is the process by which an object is held aloft, without mechanical support, in a stable position.

https://nationalmaglab.org/magnet-academy/read-science-stories/science-simplified/superconductivity-101/

BCS Theory
- the origin of superconductivity

Bardeen Cooper and Schrieffer derived two expressions that describe the mechanism that causes superconductivity,

$$|\Delta| = 2\hbar\omega_D \exp\left[-\frac{1}{N(0)V}\right]$$

$$k_B T_c = 1.14\hbar\omega_D \exp\left[-\frac{1}{N(0)V}\right]$$

where Tc is the critical temperature, Δ is a constant energy gap around the Fermi surface, N(0) is the density of states and V is the strength of the coupling.

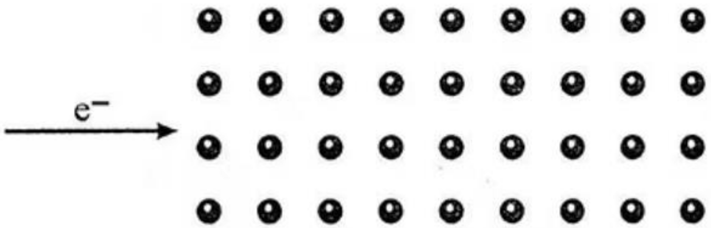
Figure 12.3: John Bardeen, Leon Cooper, and J. Robert Schrieffer.

Near Tc: $\Delta(T) = 1.734\,\Delta(0)\left(1-\frac{T}{T_c}\right)^{1/2} \simeq 3.06\,k_B T_c\left(1-\frac{T}{T_c}\right)^{1/2}$

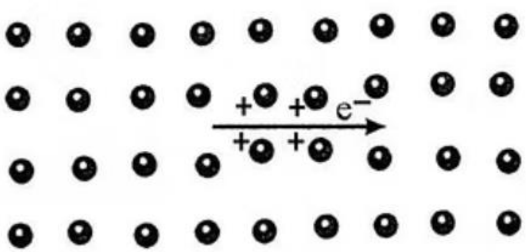
https://courses.physics.ucsd.edu/2023/Spring/physics239/LECTURES/C12.pdf

Debye Frequency

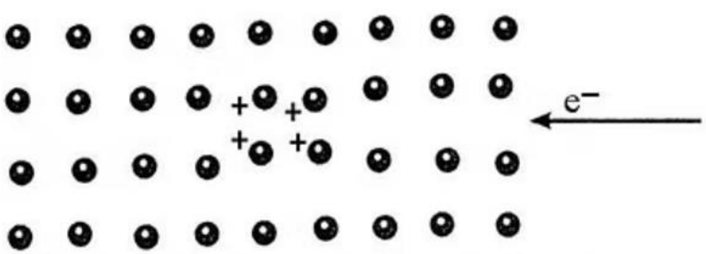
ω_D



First electron approach a section of the crystal lattice



First electrons defoms part of the lattice electrostatically.

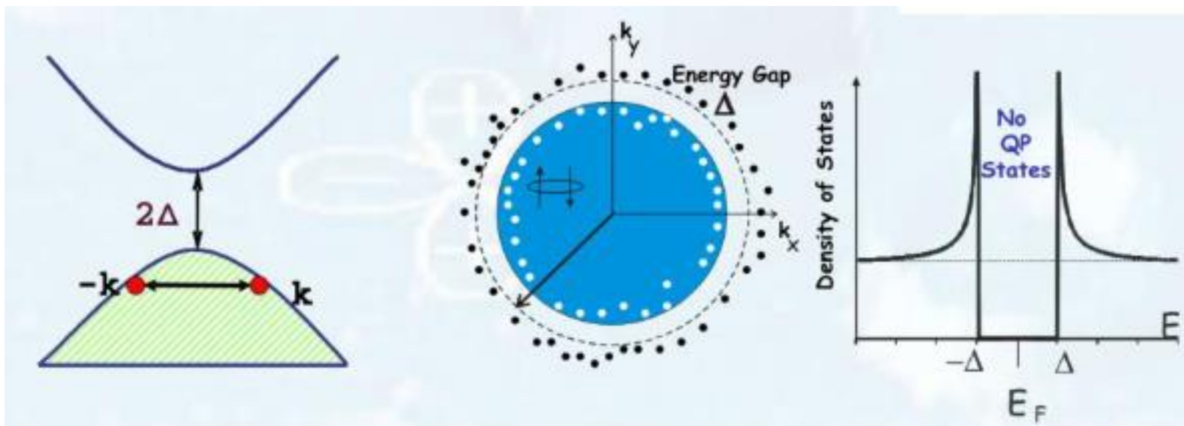


Second electron is attracted to the net positive charge of the deformation

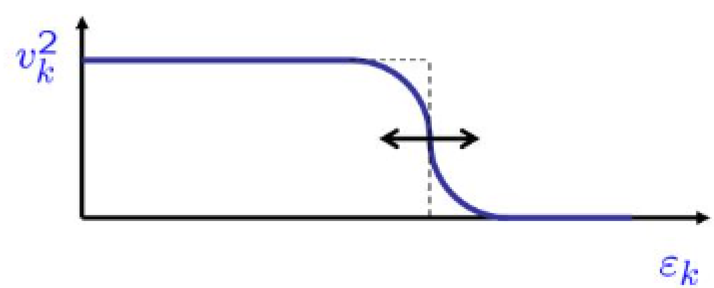
The Debye frequency represents the highest vibrational frequency of the atoms in the crystal lattice of the superconductor. There are no phonon modes above this frequency. Thus, Debye frequency is the upper limit of the phonon spectrum in the Debye model of specific heat.

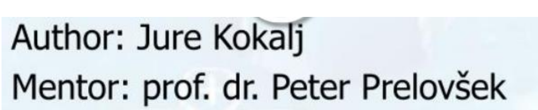
https://www.physicspower.com/post/bcs-theory

https://phys.uri.edu/~nigh/Leuven-2011/henley/7.3.pdf



$$|BCS\rangle = \prod_k (u_k + v_k a_k^\dagger a_{-k}^\dagger)|-\rangle \qquad u_k^2 + v_k^2 = 1$$





https://www.slideserve.com/connie/unconventional-superconductivity

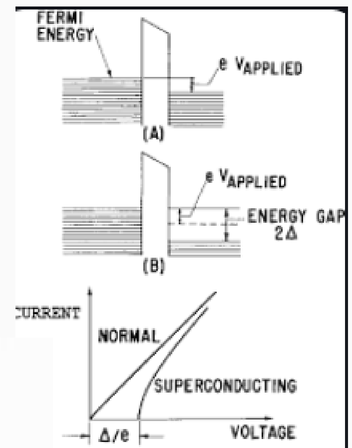
Energy gap in superconductors: Giaever junction experiment

Near Tc: $$\Delta(T) = 1.734\,\Delta(0)\left(1 - \frac{T}{T_c}\right)^{1/2} \simeq 3.06\,k_B T_c \left(1 - \frac{T}{T_c}\right)^{1/2}$$

Artificial intelligence advice:

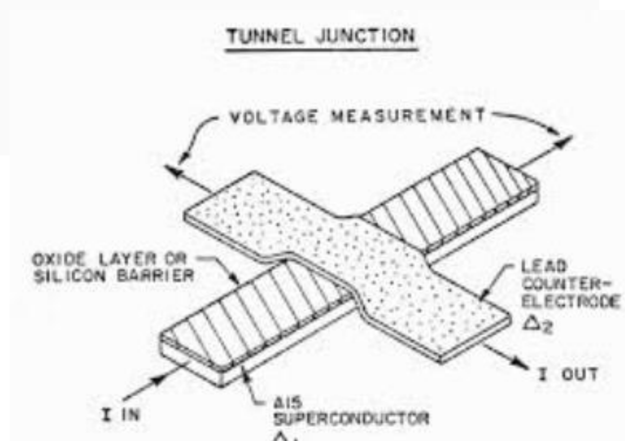
The temperature dependence of the energy gap ($\Delta(T)$) in superconductors over the entire temperature range can be described by a more precise formula derived from the BCS (Bardeen-Cooper-Schrieffer) theory. The formula is:

$$\Delta(T) = \Delta(0)\tanh\left(\frac{\pi k_B T_c}{\Delta(0)}\sqrt{\frac{T_c}{T} - 1}\right)$$



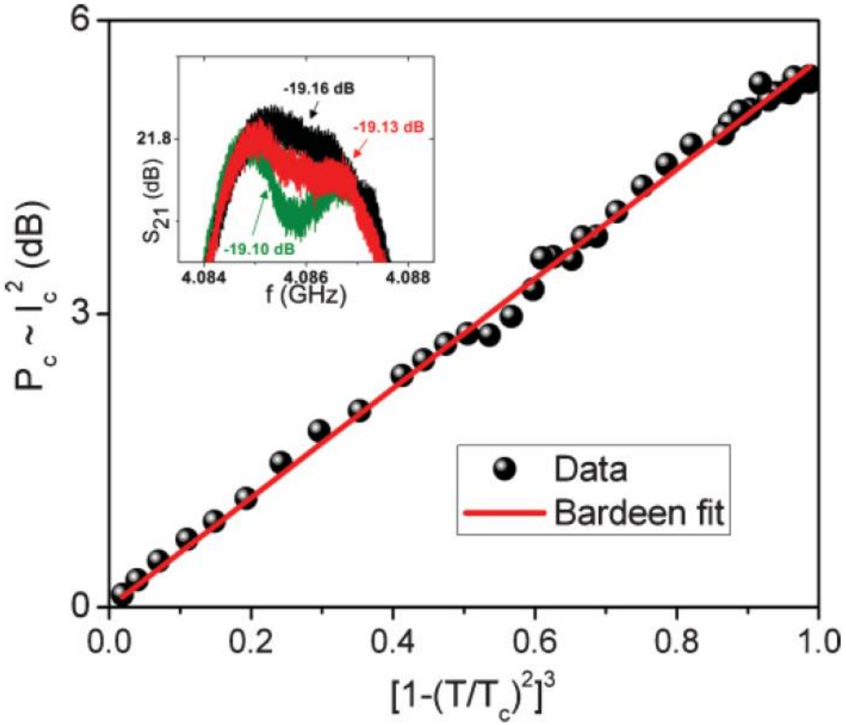
where:

- $\Delta(0)$ is the energy gap at absolute zero temperature,
- T is the temperature,
- T_c is the critical temperature,
- k_B is the Boltzmann constant.



Bardeen formula for the critical current of a thin superconducting wire

$$I_c = I_c(0)[1 - (T/T_c)^2]^{3/2}$$



Superconducting resonator method

Matthew W. Brenner, Sarang Gopalakrishnan, Jaseung Ku, Timothy J. McArdle, James N. Eckstein, Nayana Shah, Paul M. Goldbart, and Alexey Bezryadin, PHYSICAL REVIEW B **83**, 184503

BCS theory

- Gap and order parameter

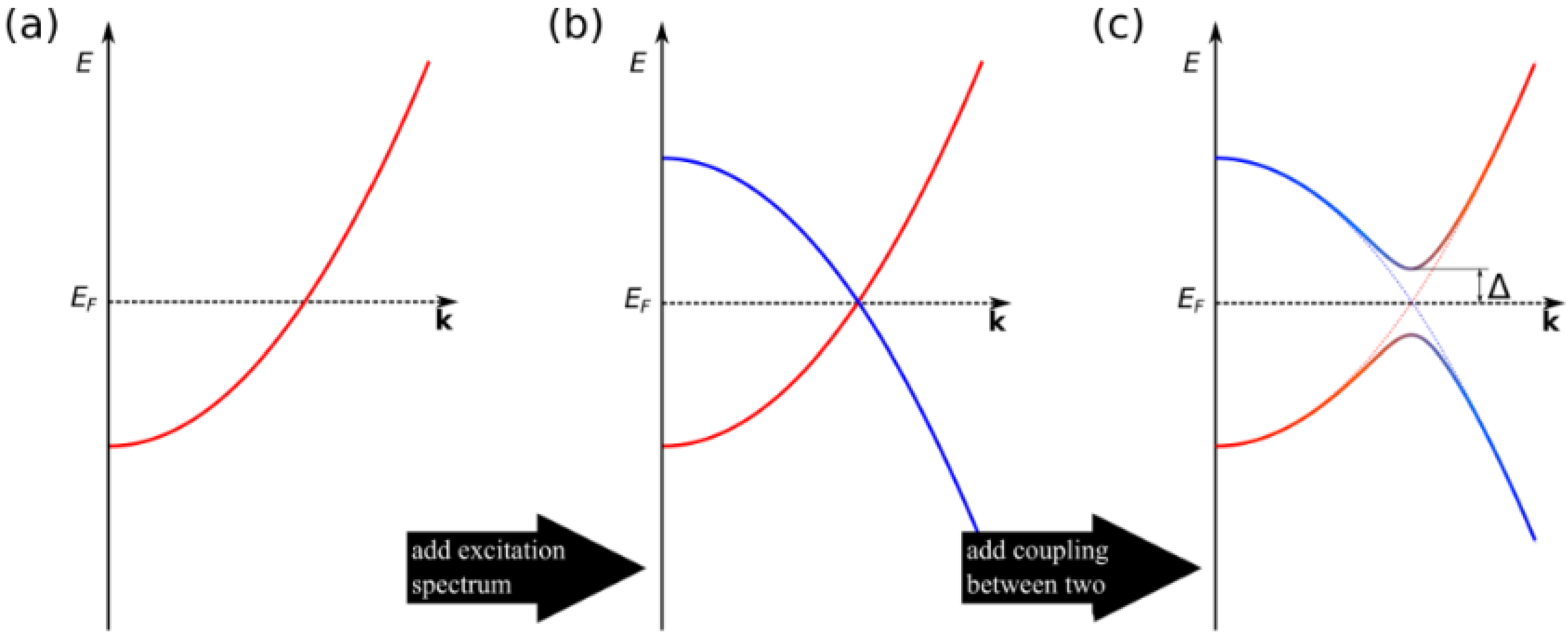
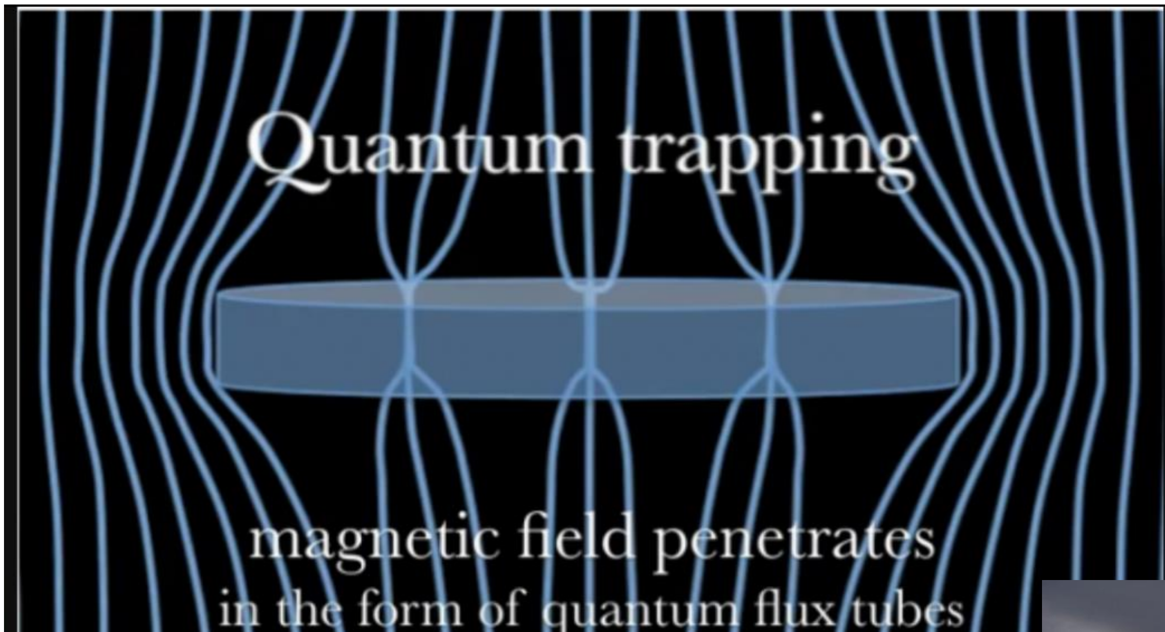


*Figure 1: **BCS theory: example of electron and hole bands coupling.** (a) a parabolic electron-like band, (b) add the excitation hole-like band, (c) superconducting gap opens when the electron-like and hole-like bands are coupled by an interaction Δ.*

https://shunchi100.wordpress.com/superconductivity-and-its-pairing-symmetry/mean-field-approximation-to-bcs-hamiltonian/

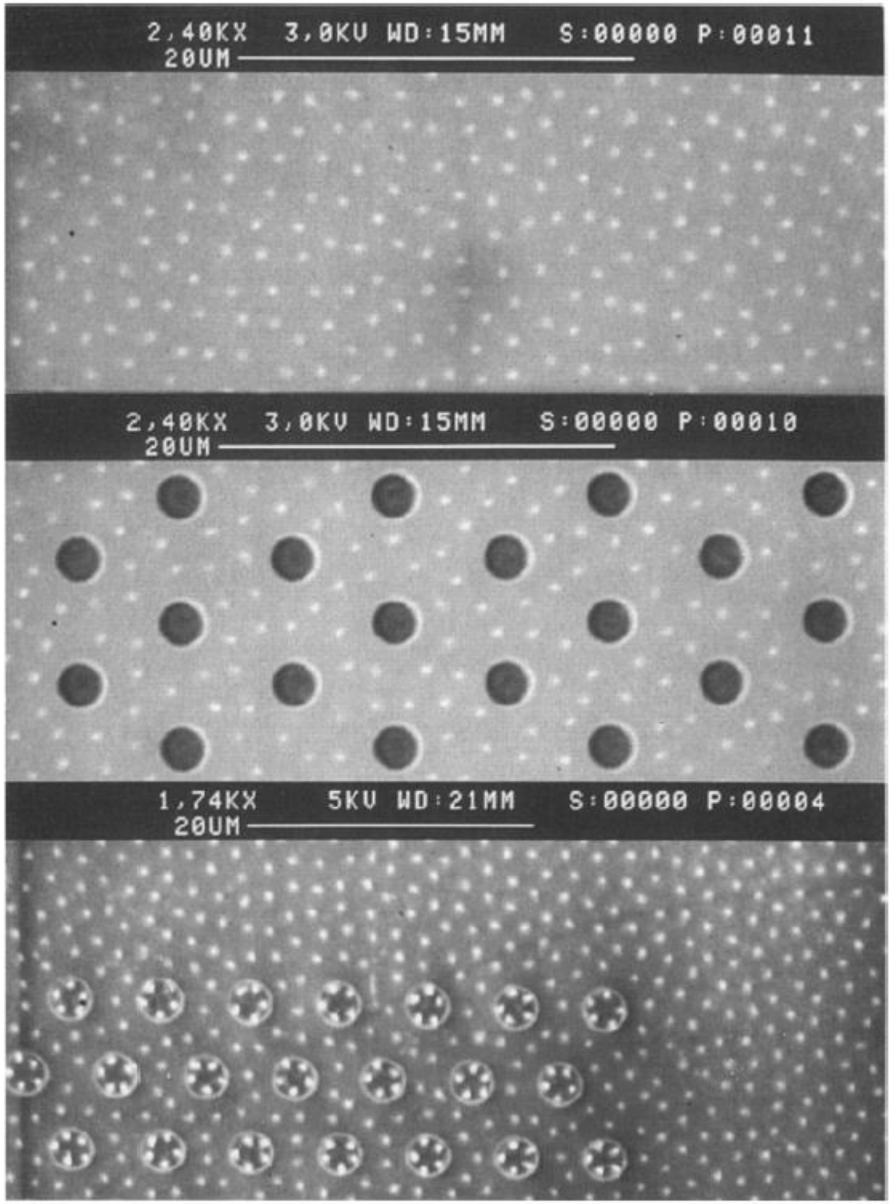
Magnetic field effect: Superconducting vortices



In superconductivity, a **fluxon** (also called an **Abrikosov vortex** or **quantum vortex**) is a vortex of supercurrent in a type-II superconductors

https://blog.tmcnet.com/blog/tom-keating/technology-and-science/quantum-levitation-back-to-the-future-hoverboard.asp

Vortices in superconducting films with "through" and "blind" holes ("antidots")



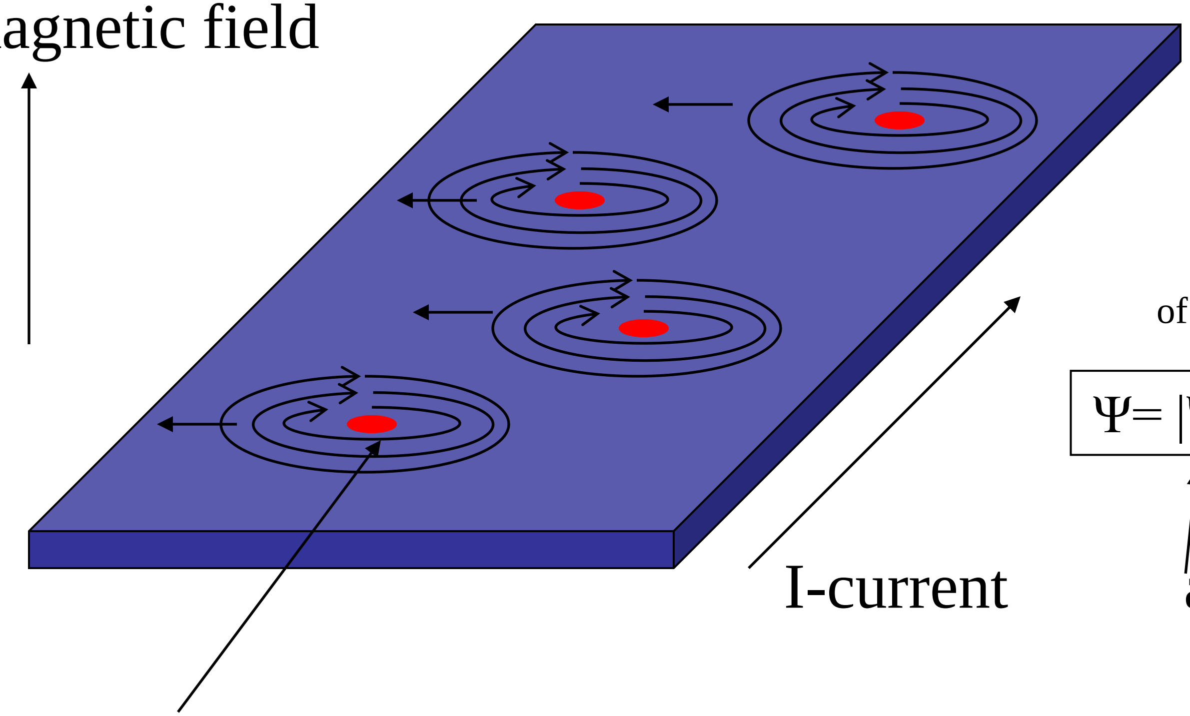
A. Bezryadin and B. Pannetier
"Role of Edge Superconducting States in Trapping of Multi-Quanta Vortices by Microholes. Application of the Bitter Decoration Technique",
J. Of Low Temp. Phys., V.102, p.73 (1996).

Vortices are quantized tubes carrying magnetic field into superconductor

Magnetic field creates vortices--

Vortices cause dissipation (i.e. a non-zero electrical resistance), if they move

B -magnetic field



I-current

Wave function of all superconducting electrons:

$$\Psi = |\Psi| \exp(i\varphi) = |\Psi| \exp(i\theta)$$

amplitude

phase

Vortex core (red): normal, not superconducting; diameter ξ~10 nm

The current is extended to a scale λ, which is larger than ξ in type II superconductors (such as thin films of any material)

Reminder: single electron in empty space

Wave function: $\Psi = |\Psi| \exp(ikx) = |\Psi| [\cos(kx) + i \sin(kx)]$

Wave number: $k=2\pi/\lambda$

$i*i=-1$

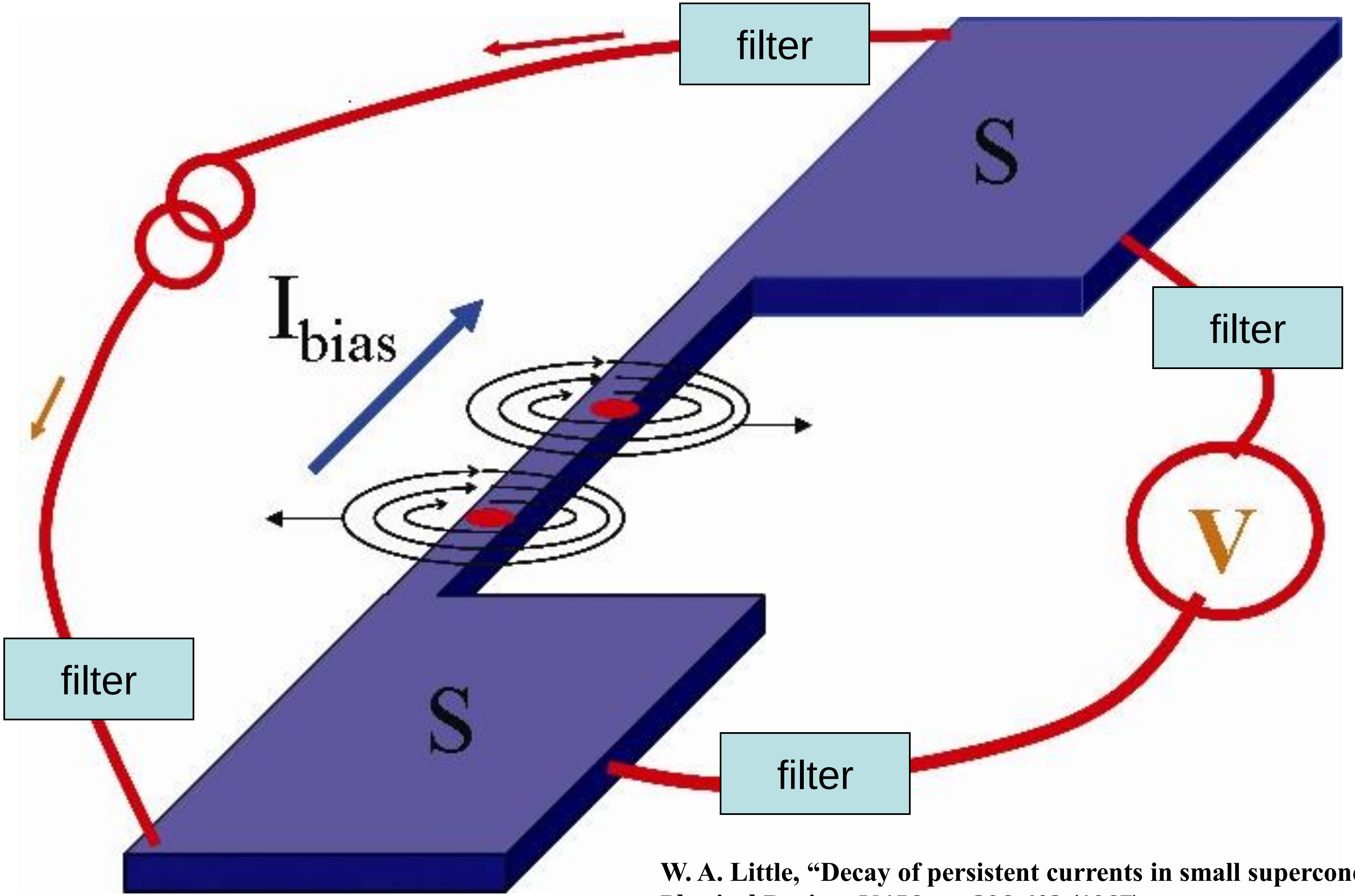
General form: $\Psi = |\Psi| \exp(-i\varphi)$

In this example of a plane wave, the phase is: $\varphi=kx$

DC transport measurement schematic to detect passing vortices

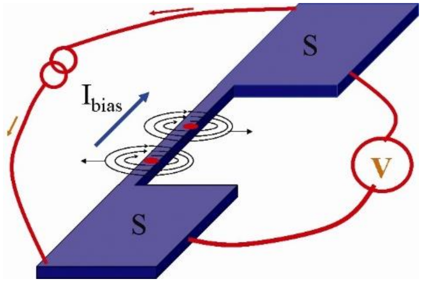
Bleu: superconducting film and wire

Red: Phase slip events or crossing vortices



W. A. Little, “Decay of persistent currents in small superconductors”, Physical Review, V.156, pp.396-403 (1967).

How to use voltage to determine the rate of phase slips?



Key principle: every time a vortex crosses the wire the phase difference changes by 2π.

Phase evolution equation: $d\varphi/dt = 2eV/\hbar$

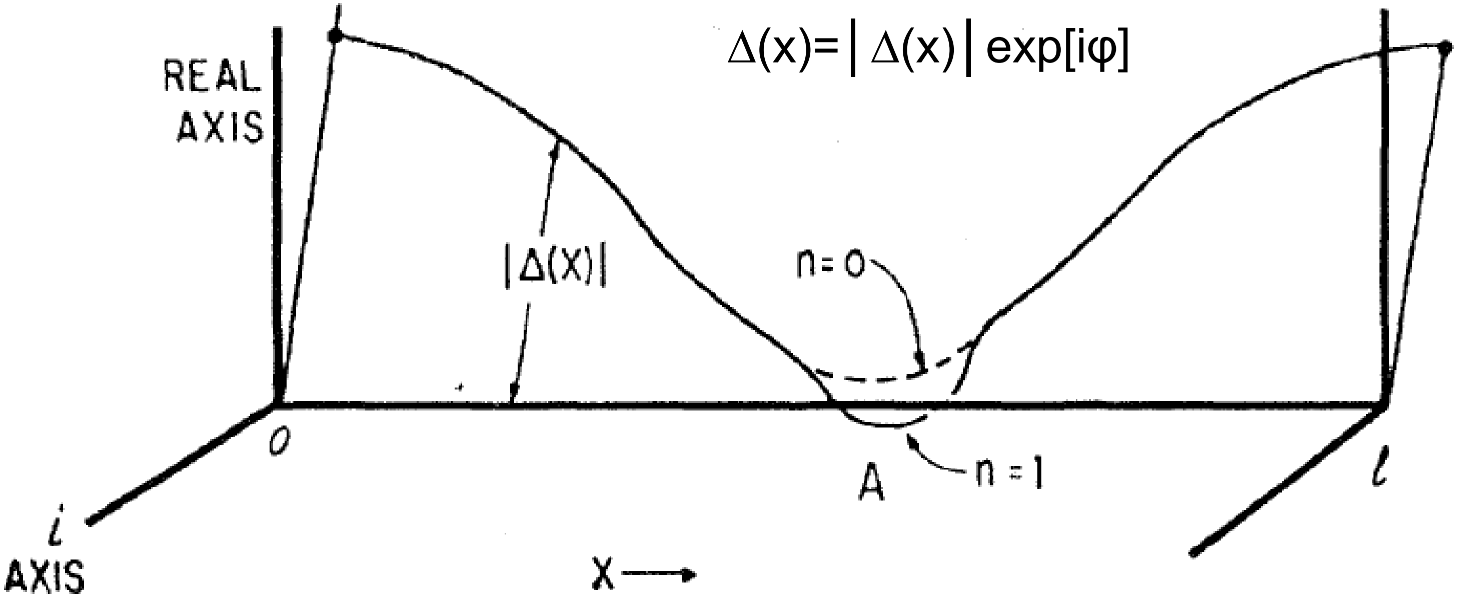
Simplified derivation:

1. Time-dependent Schrödinger equation with fixed energy:
$i\hbar(d\Psi/dt)=E\,\Psi$
2. The solution is: $\Psi=\exp(-iEt/\hbar)$ (here E is the energy)
3. The phase of the wavefunction is $\varphi=Et/\hbar$
4. The energy is defined by the electric potential (voltage), V as follows: $E=2eV$. Note that the effective charge of superconducting electrons is 2e, where "e" is the charge of one electron. Such superconducting electron pairs are called Cooper pairs.

Thus, the resulting equation is: $d\varphi/dt = 2eV/\hbar$

Gor'kov, L.P. (1958) *Sov. Phys. JETP*, **7**, 505.

Thin superconducting wire have some nonzero electrical resistance due to Little's Phase Slips



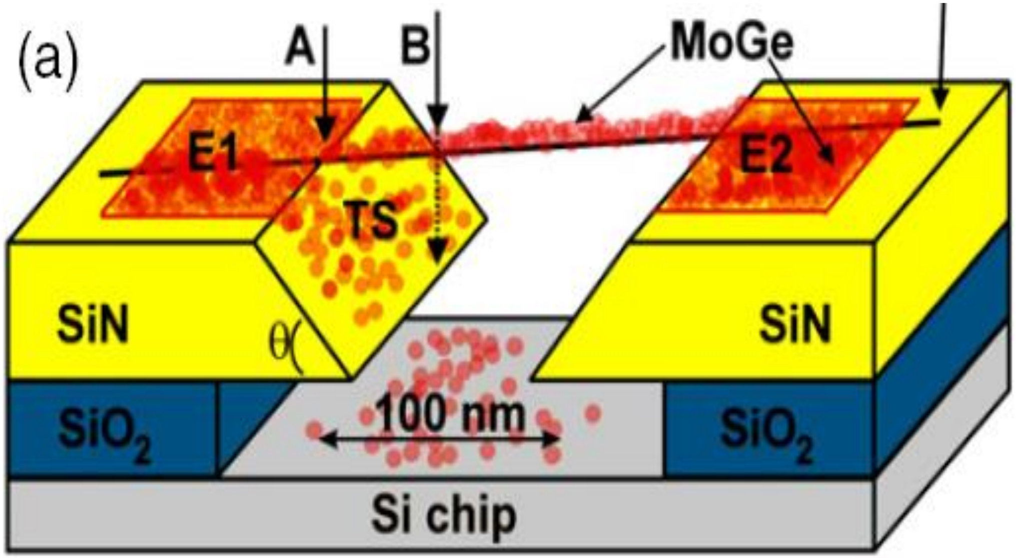
W. A. Little, "Decay of persistent currents in small superconductors", Physical Review, V.156, pp.396-403 (1967).

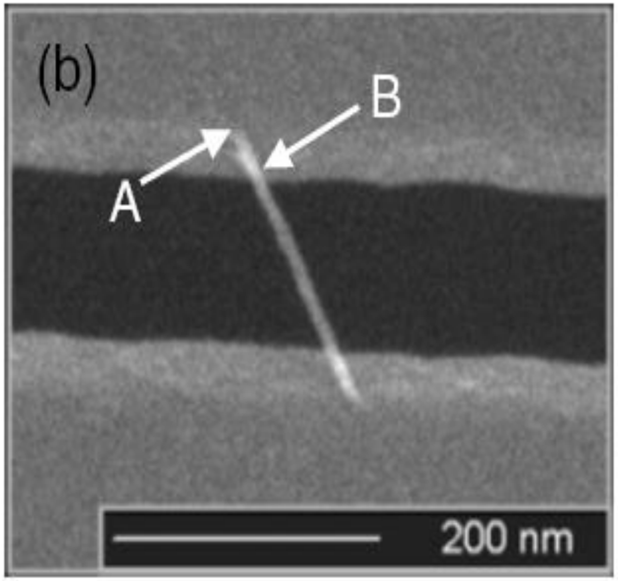
Two types of phase slips (PS) can occur:

1. The usual, thermally activated PS (TAPS)
2. Quantum phase slip (QPS)

Fabrication of nanowires

Method of Molecular Templating





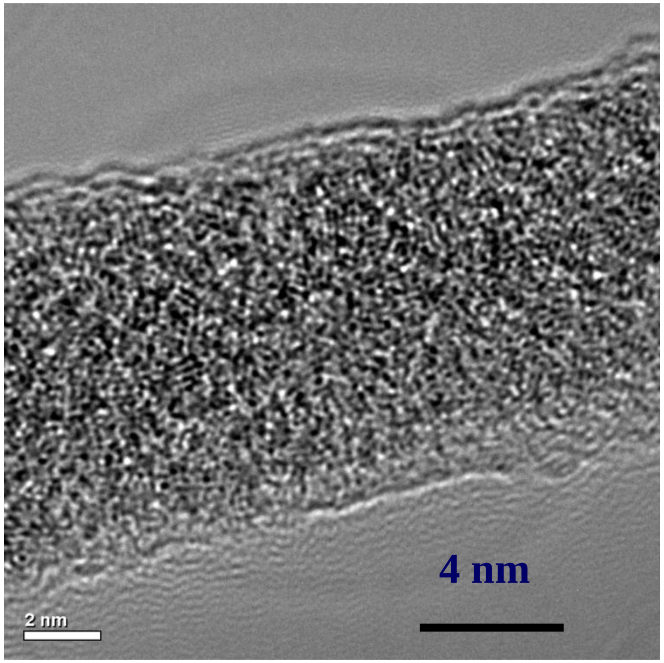
Si/ SiO_2/SiN substrate with undercut

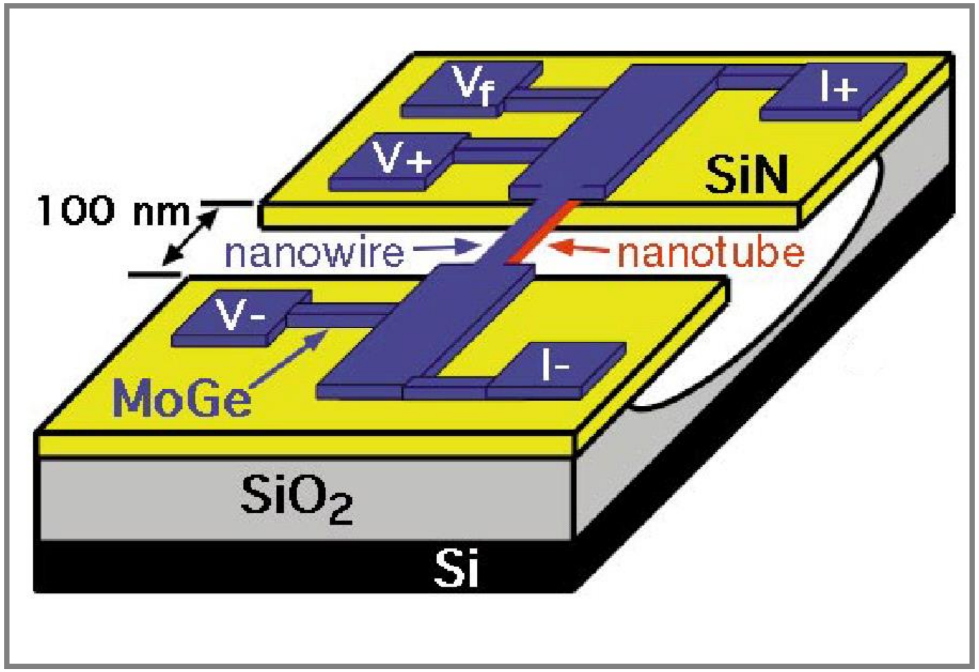
~ 0.5 mm Si wafer
500 nm SiO_2
60 nm SiN
Width of the trenches ~ 50 - 500 nm

HF wet etch for ~10 seconds to form undercut

Bezryadin, Lau, Tinkham, *Nature* **404**, 971 (2000)

Sample Fabrication





TEM image of a wire shows amorphous wire morphology.
Nominal MoGe thickness = 3 nm

Schematic picture of the pattern Nanowire + Film Electrodes used in transport measurements

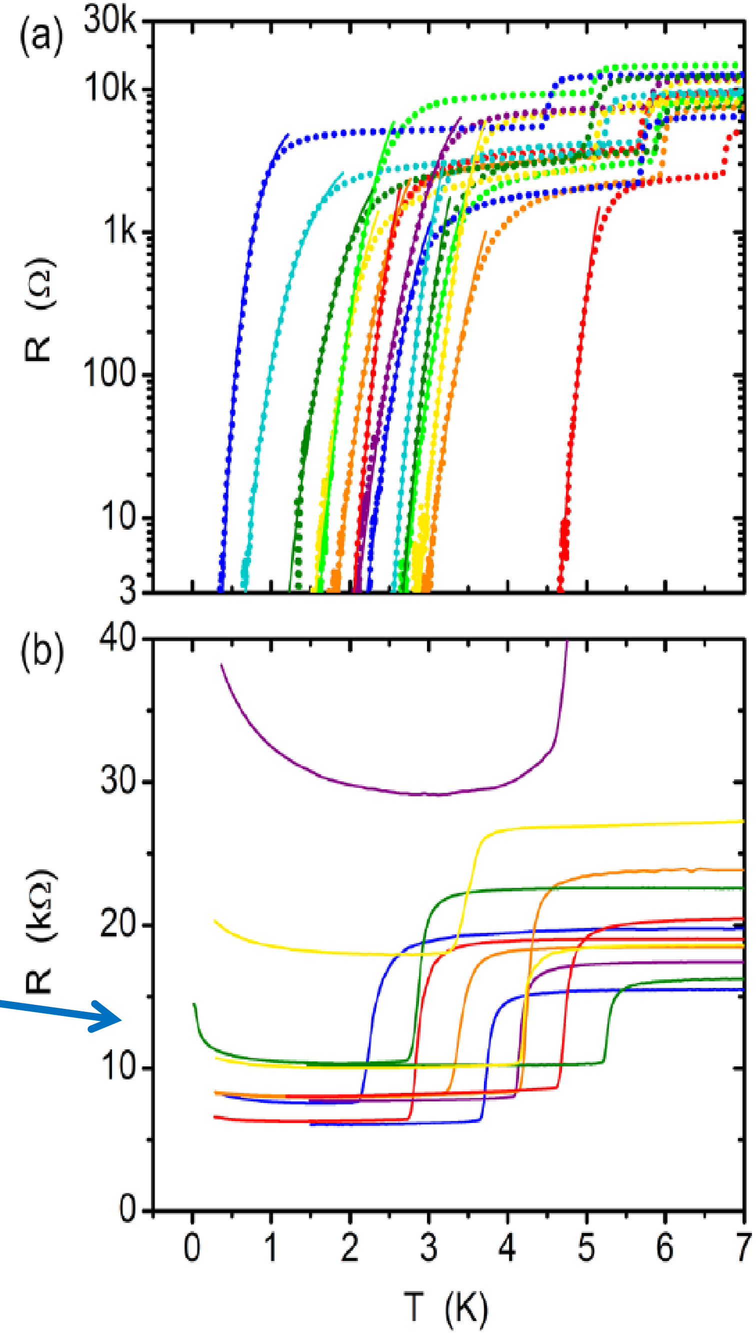
Dichotomy in nanowires: Evidence for superconductor-insulator transition (SIT)

R=V/I I~3 nA

The difference between samples is the amount of the deposited Mo79Ge21.

Thin wires become insulating if their normal resistance is lager than resistance quantum h/4/e/e=6.5KOhm

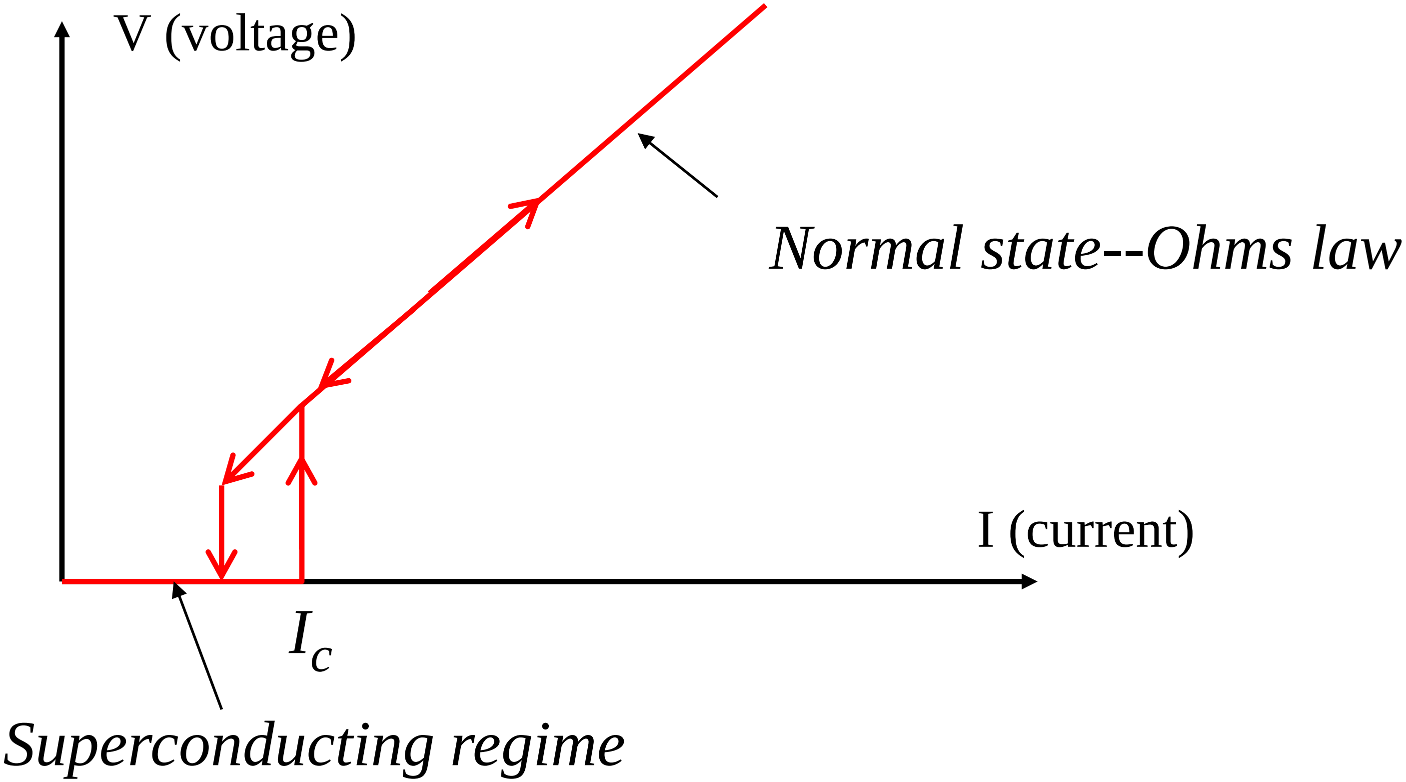
The insulating behavior is due to proliferation of quantum phase slips



Bollinger, Dinsmore, Rogachev, Bezryadin, Phys. Rev. Lett. **101**, 227003 (2008)

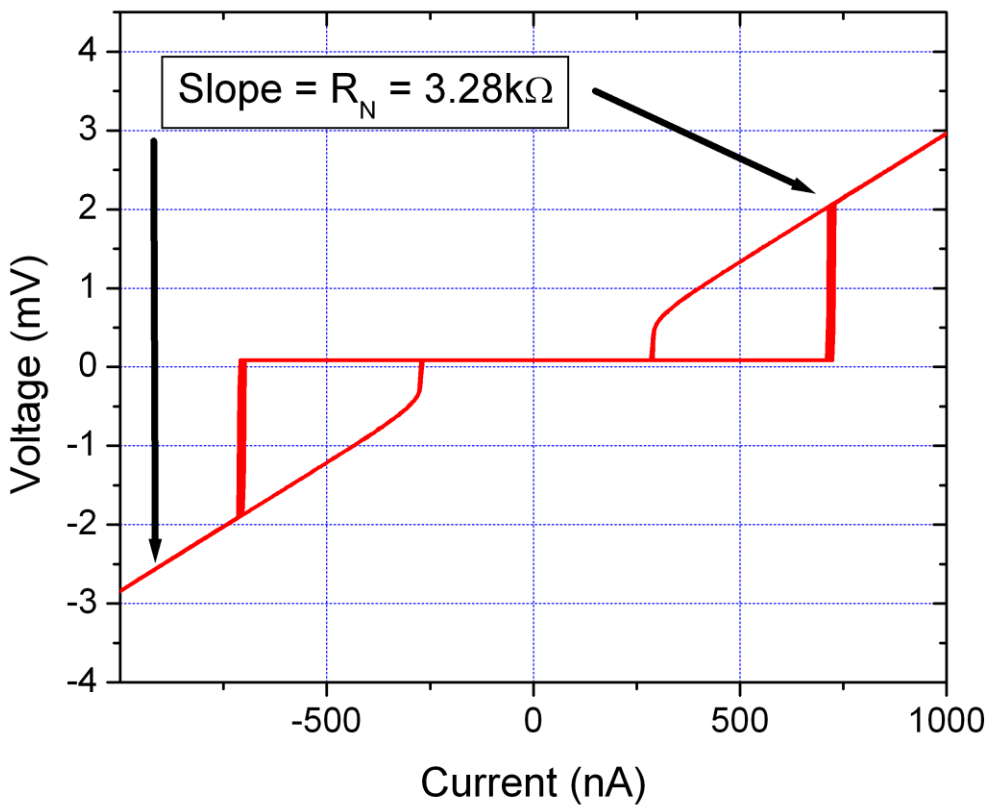
Expected voltage-current curve

Electrical resistance is zero only if current is not too strong

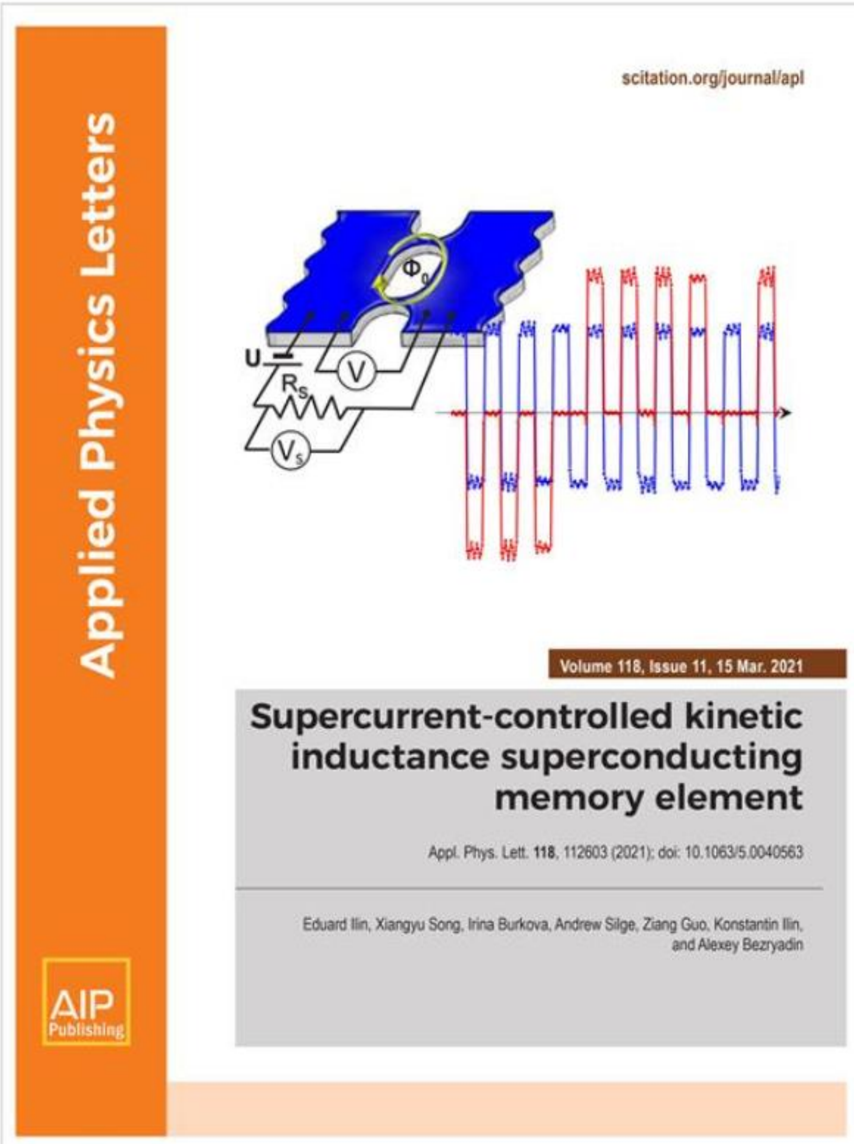


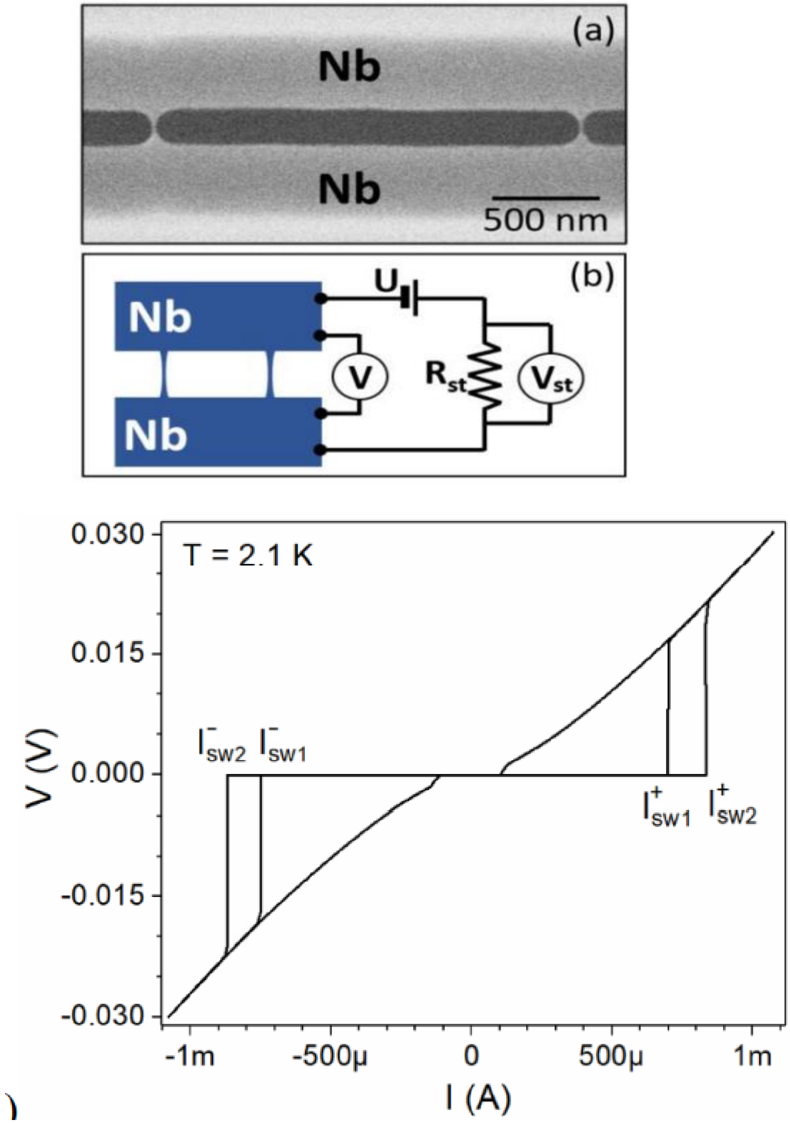
Experimental voltage-current curve.

Fluctuations of the switching current are due to Little's phase slips



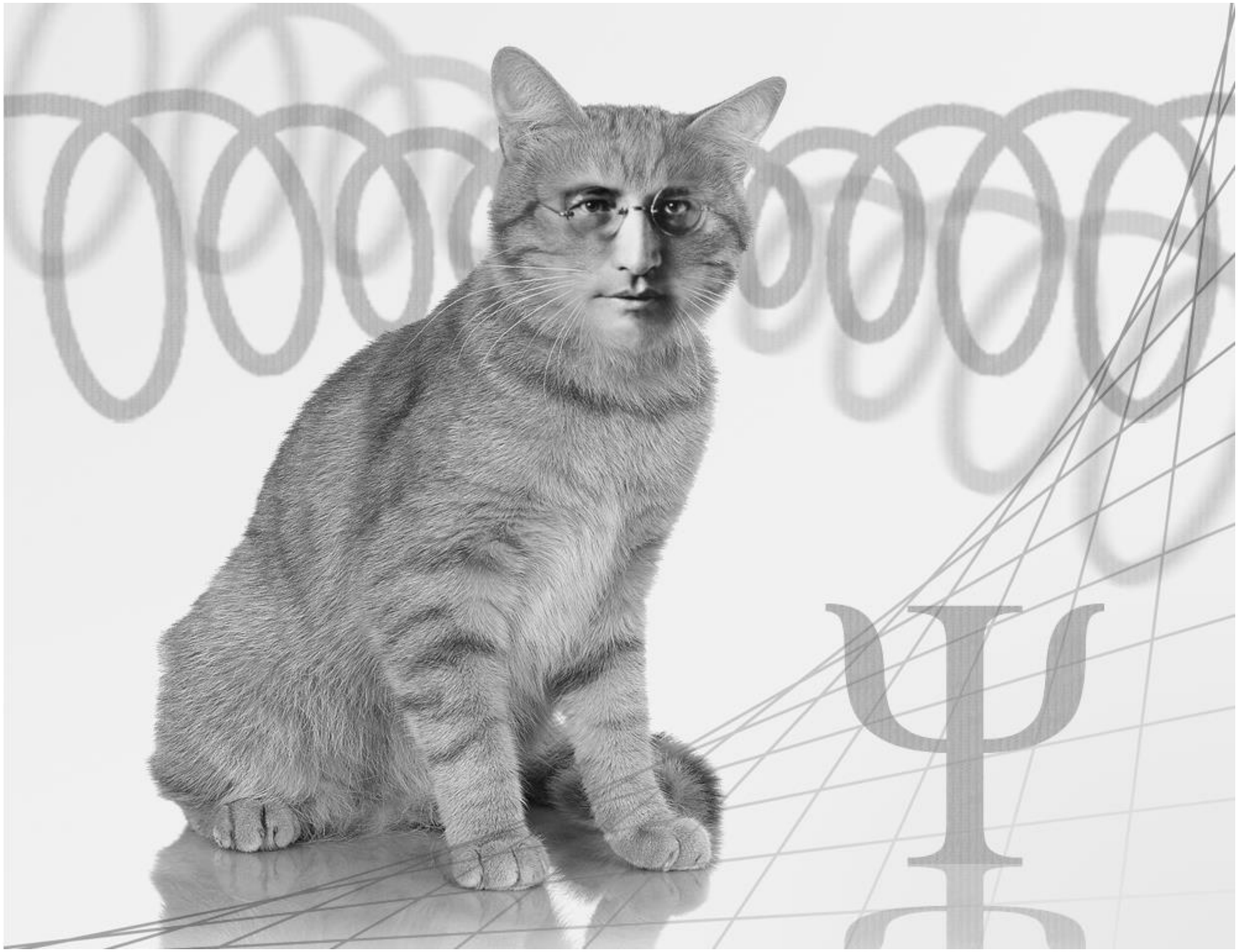
Superconducting nanowire memory



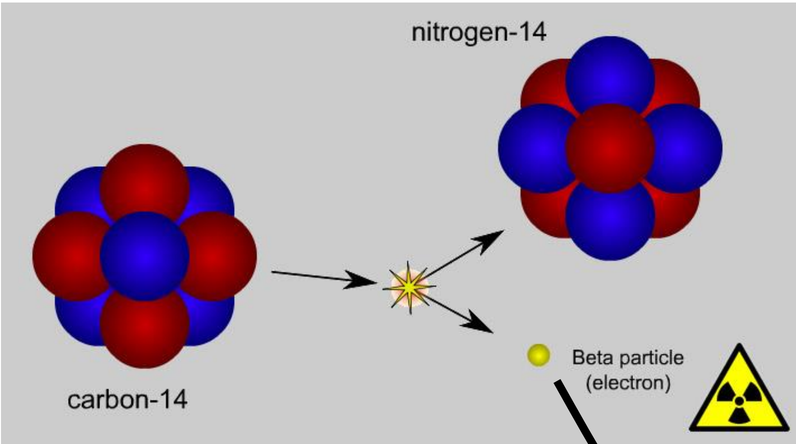


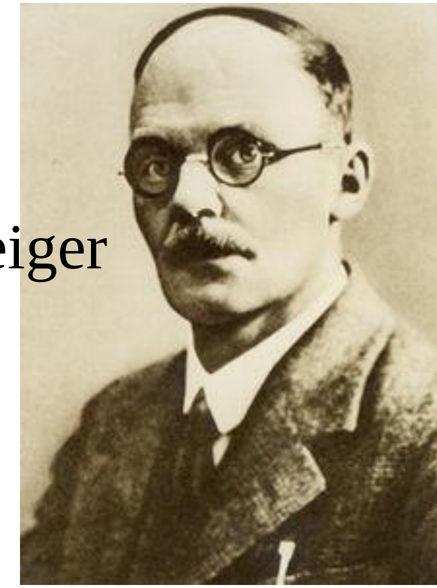
Schrödinger cat –
the ultimate macroscopic quantum phenomenon

E. Schrödinger, Naturwiss. **23** (1935), 807.



Schrödinger cat – thought experiment





Hans Geiger

Geiger counter

Linearity of the Schrödinger's equation

Suppose Ψ_1 is a valid solution of the Schrödinger equation:

$$i\hbar\frac{\partial\psi_1}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi_1}{\partial x^2} + U(x)\psi_1$$

And suppose that Ψ_2 is another valid solution of the Schrödinger equation:

$$i\hbar\frac{\partial\psi_2}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi_2}{\partial x^2} + U(x)\psi_2$$

Then $(\Psi_1 + \Psi_2)/\sqrt{2}$ is also a valid solution, because:

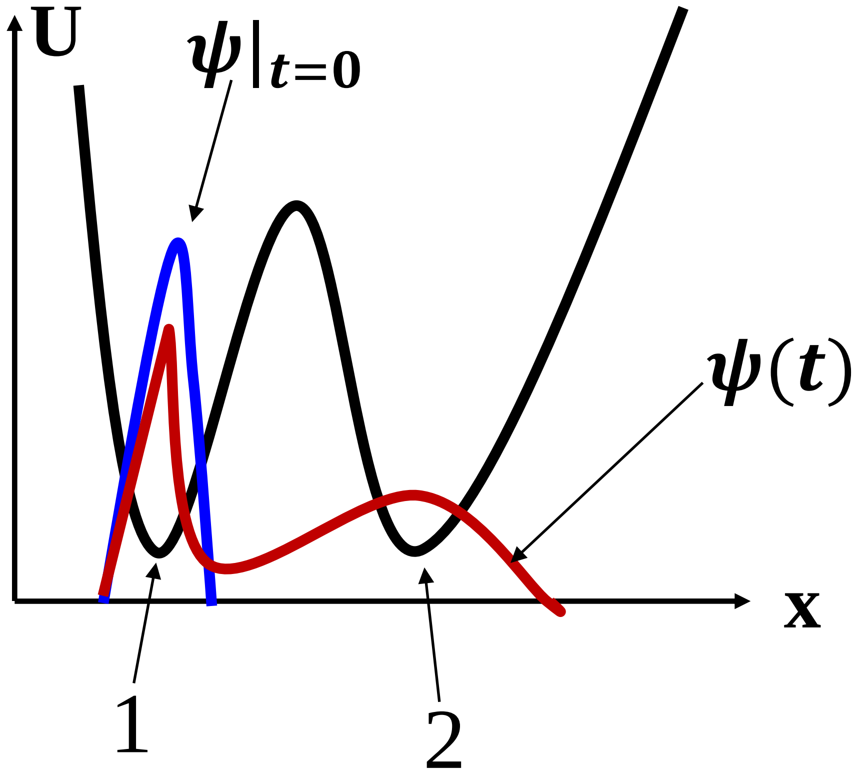
$$i\hbar\frac{\partial(\psi_1+\psi_2)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2(\psi_1+\psi_2)}{\partial x^2} + U(x)(\psi_1+\psi_2)$$

The state $(\Psi_1 + \Psi_2)/\sqrt{2}$ is a new combined state which is called "quantum superposition" of state (1) and (2)

George Gamow

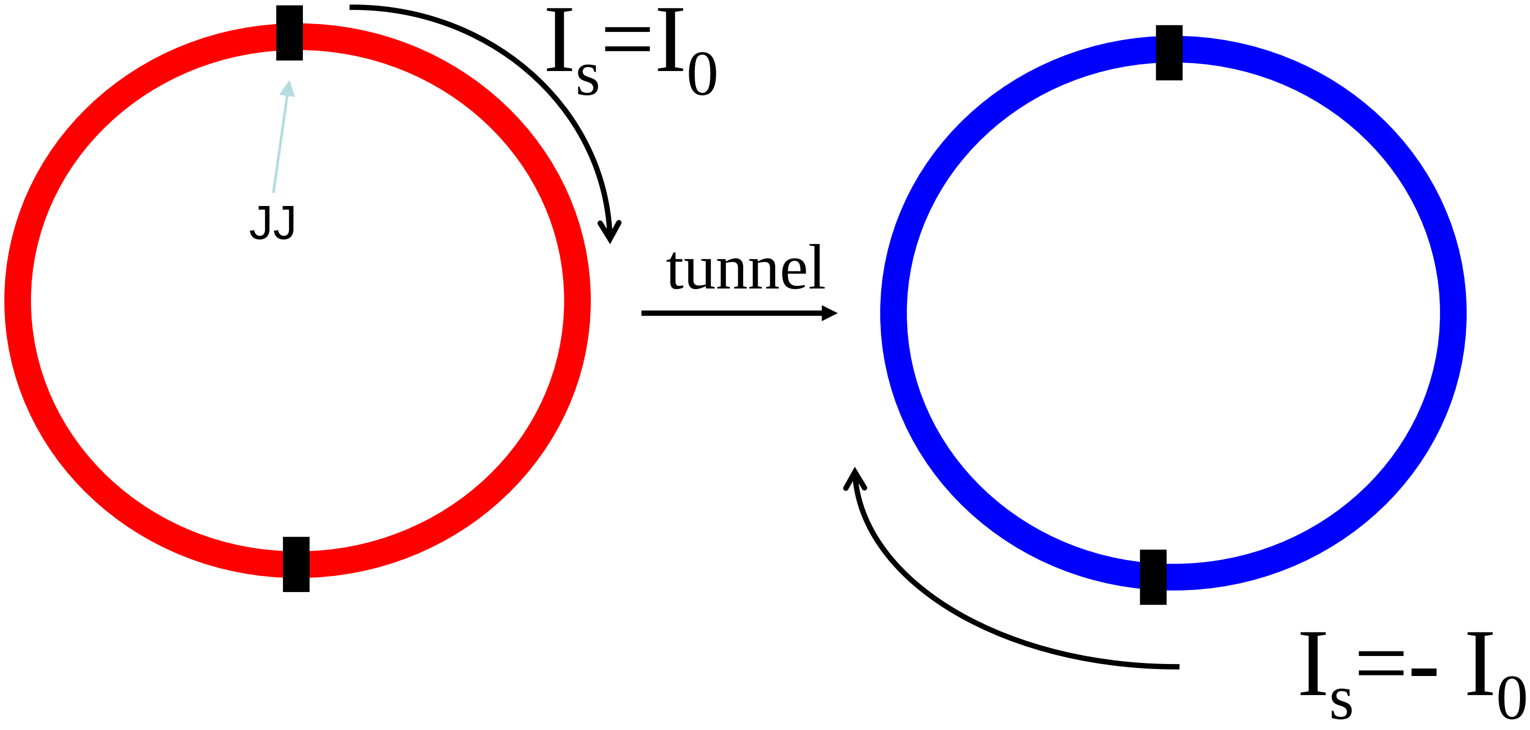
(He also helped to developed
Big Bang theory)

Quantum tunneling



Quantum tunneling is possible since quantum superpositions of states are possible.

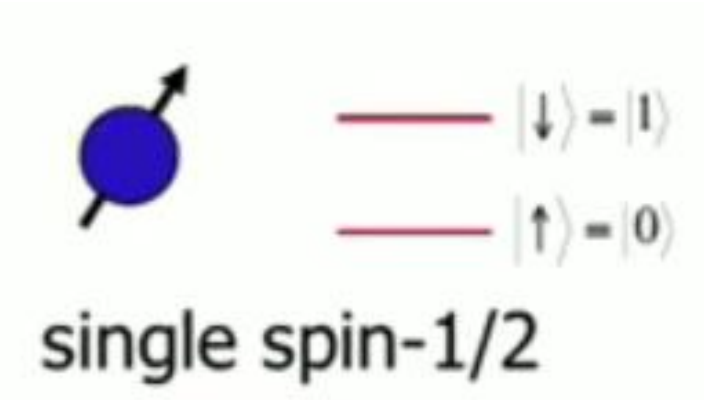
What sort of tunneling we will consider?

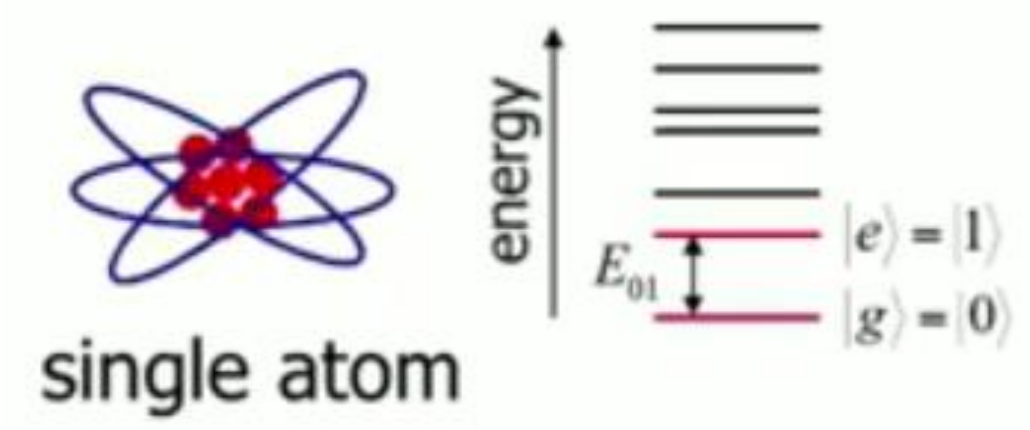


-Red color represents some strong current in the superconducting wire loop

-Blue color represents zero current in the loop

Types of Qubit



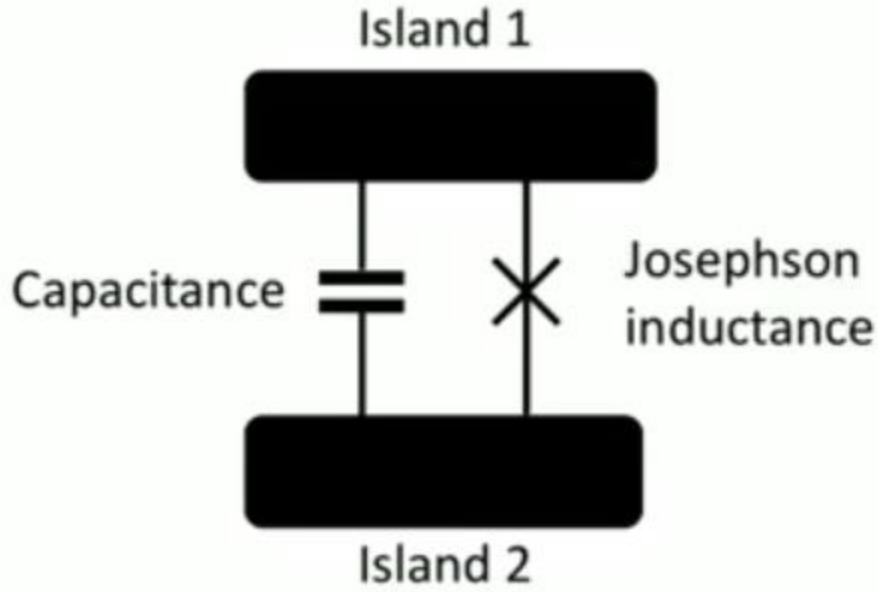


Quantum state:
|ψ>=A*|0>+B*|1>

$A^2+B^2=1$

A and B are complex numbers

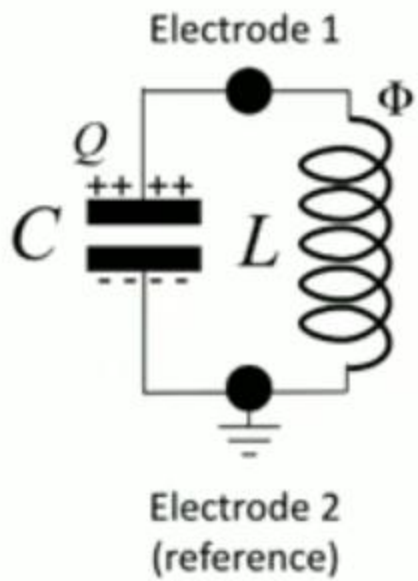
Transmon Qubit



Theory of transmons: J. Koch et al., Phys. Rev. A **76**, 042319 (2007).

Quantization of electrical circuits

The quantized *LC* oscillator



Hamiltonian:

$$\hat{H}_{LC} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$

Capacitive term ↗ ↖ Inductive term

Canonically conjugate variables:

$\hat{\Phi}$ = Flux through the inductor.

$\hat{Q}$ = Charge on capacitor plate.

$$\left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

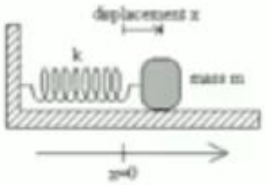
M. Devoret, Les Houches Session LXIII (1995)

Discrete energy spectrum of the LC-circuit

Correspondence with simple harmonic oscillator

$$\hat{H}_{\mathrm{LC}} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C} \qquad \left[\hat{\Phi},\hat{Q}\right] = i\hbar$$

$$\hat{H}_{\mathrm{SHO}} = \frac{k\hat{X}^2}{2} + \frac{\hat{P}^2}{2m} \qquad \left[\hat{X},\hat{P}\right] = i\hbar$$



Correspondence:

$$\hat{\Phi} \leftrightarrow \hat{X} \qquad L \leftrightarrow \frac{1}{k}$$

$$\hat{Q} \leftrightarrow \hat{P} \qquad C \leftrightarrow m$$

$$\omega = \frac{1}{\sqrt{LC}} \leftrightarrow \sqrt{\frac{k}{m}}$$

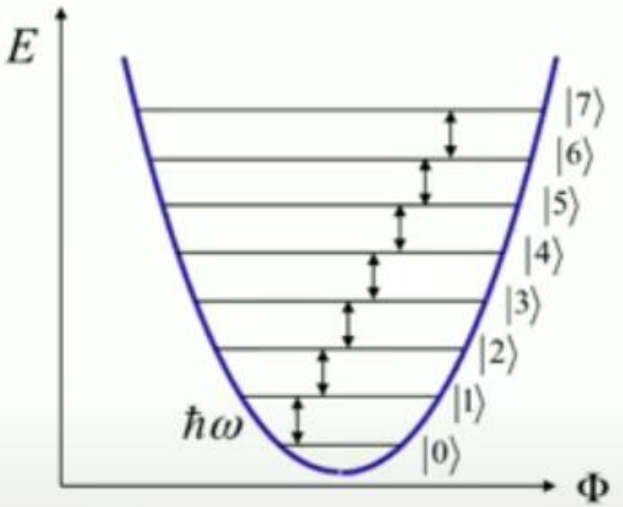
Solve using ladder operators:

$$\hat{a} = \left(\frac{\hat{Q}}{Q_{zpf}} - i\frac{\hat{\Phi}}{\Phi_{zpf}}\right) \qquad \Phi_{zpf} = \sqrt{2\hbar Z}$$

$$\hat{a}^\dagger = \left(\frac{\hat{Q}}{Q_{zpf}} + i\frac{\hat{\Phi}}{\Phi_{zpf}}\right) \qquad Q_{zpf} = \sqrt{2\hbar / Z}$$

$$Z = \omega L = \frac{1}{\omega C} = \sqrt{\frac{L}{C}}$$

$$\hat{H}_{\mathrm{LC}} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) \qquad \left[\hat{a}_r,\hat{a}_r^\dagger\right] = 1$$



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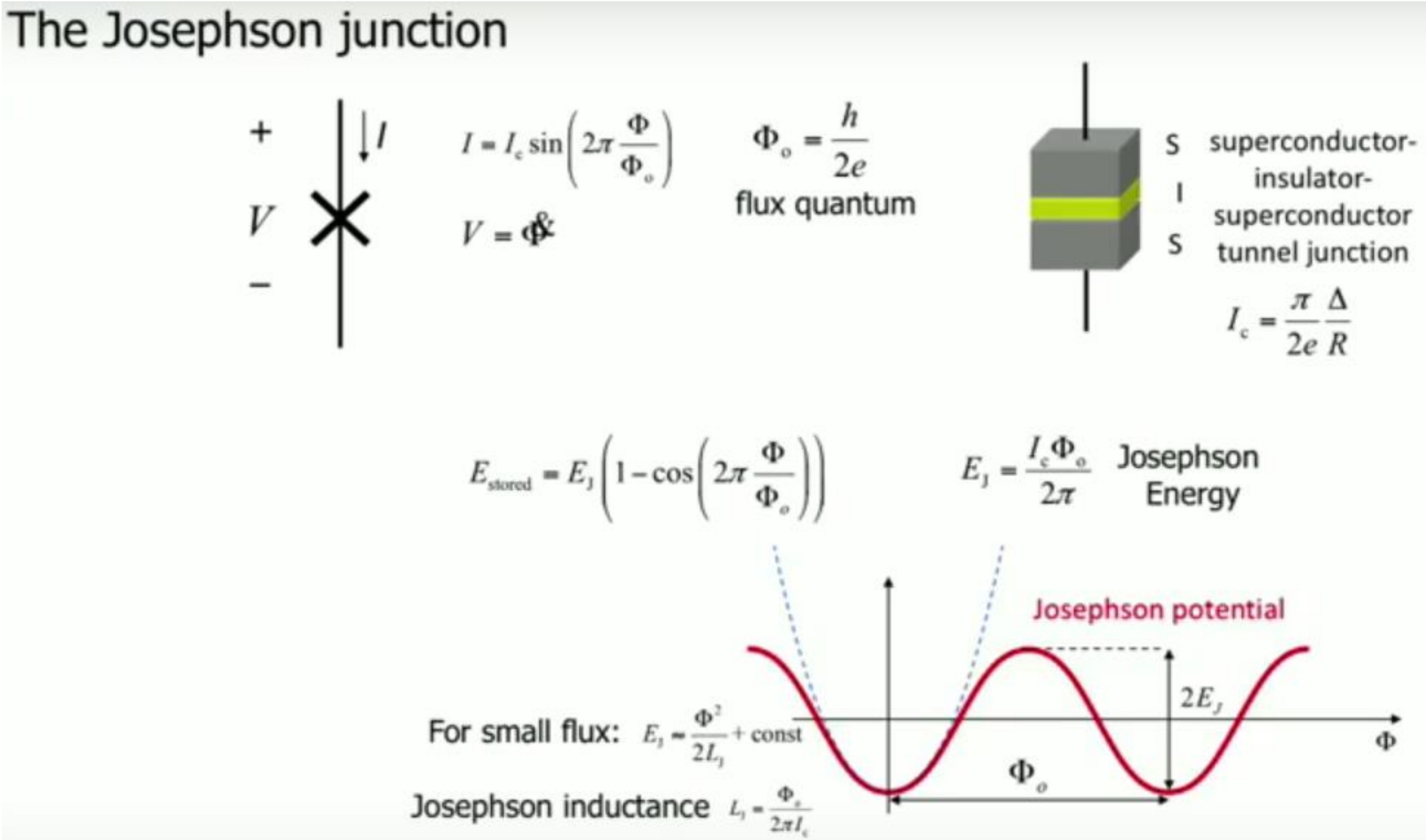
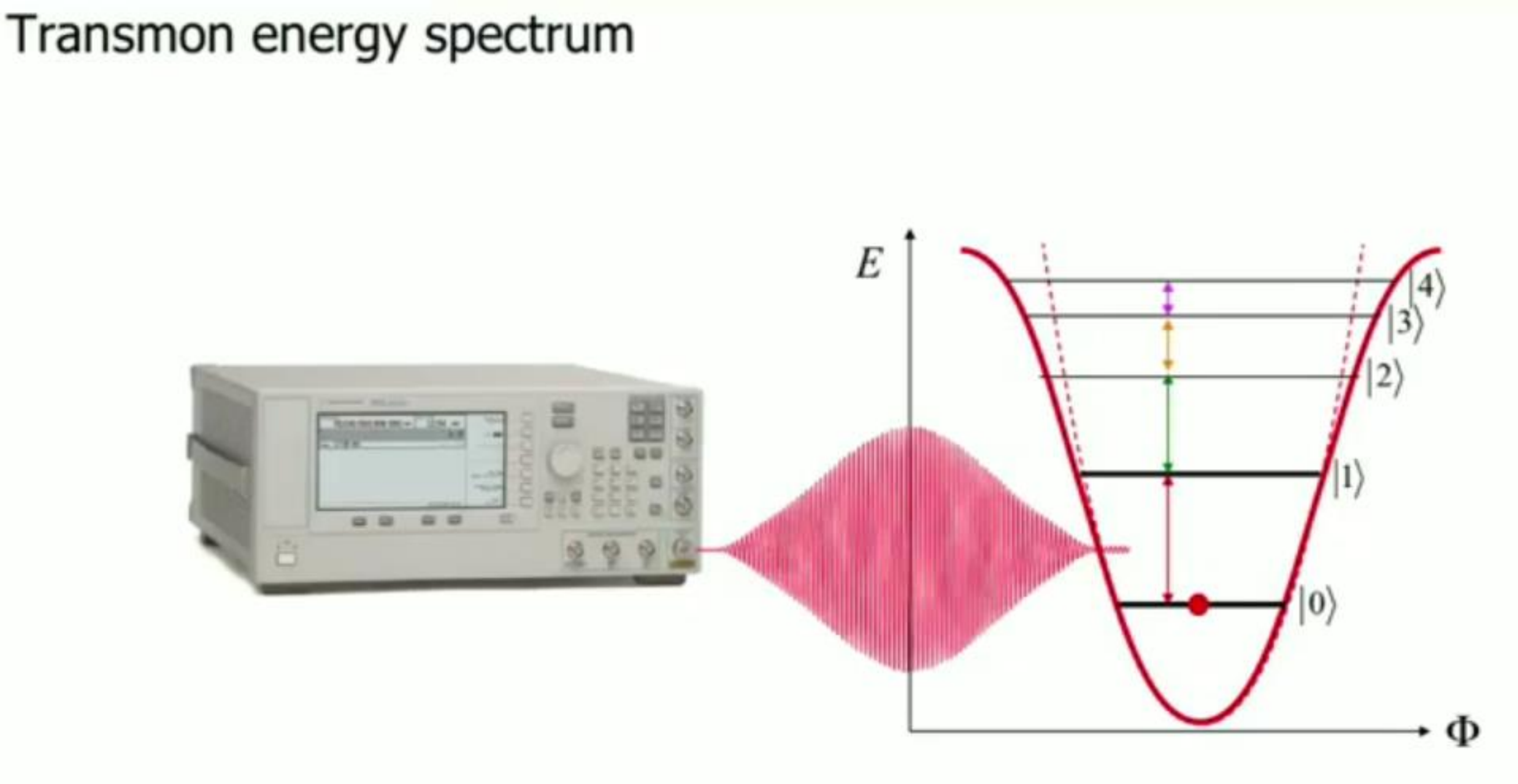
Non-harmonicity is the key factor



M. Devoret, Les Houches Session LXIII (1995)

Non-harmonicity is the key factor



Meisnerron-transmon qubit

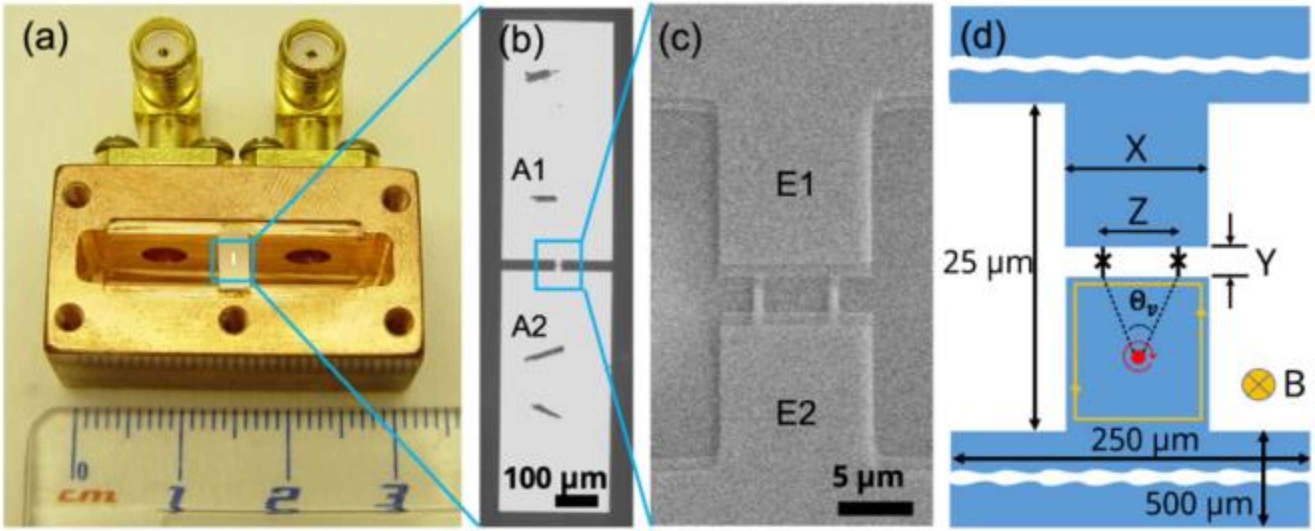


FIG. 1. (a) Optical image of the Meissner transmon qubit fabricated on a sapphire chip, which is mounted in the copper cavity. (b) A zoomed-in optical image of the qubit. Two rectangular pads marked A1 and A2 act as an RF antenna and shunt capacitor. (c) Scanning electron microscope (SEM) image of the electrodes marked E1 and E2, and a pair of JJs. (d) Schematics of the Meissner qubit. The X, Y, and Z denote the width, the distance between the electrodes, and the distance between two JJs, which are indicated by × symbols. The red dot and circular arrow around it in the bottom electrode represent a vortex and vortex current flowing clockwise, respectively. Θ_v is a polar angle defined by two dashed lines connecting the vortex and two JJs. The orange rectangular loop on the boundary of the bottom electrode indicates the Meissner current circulating counterclockwise.

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Meisnerron-transmon qubit

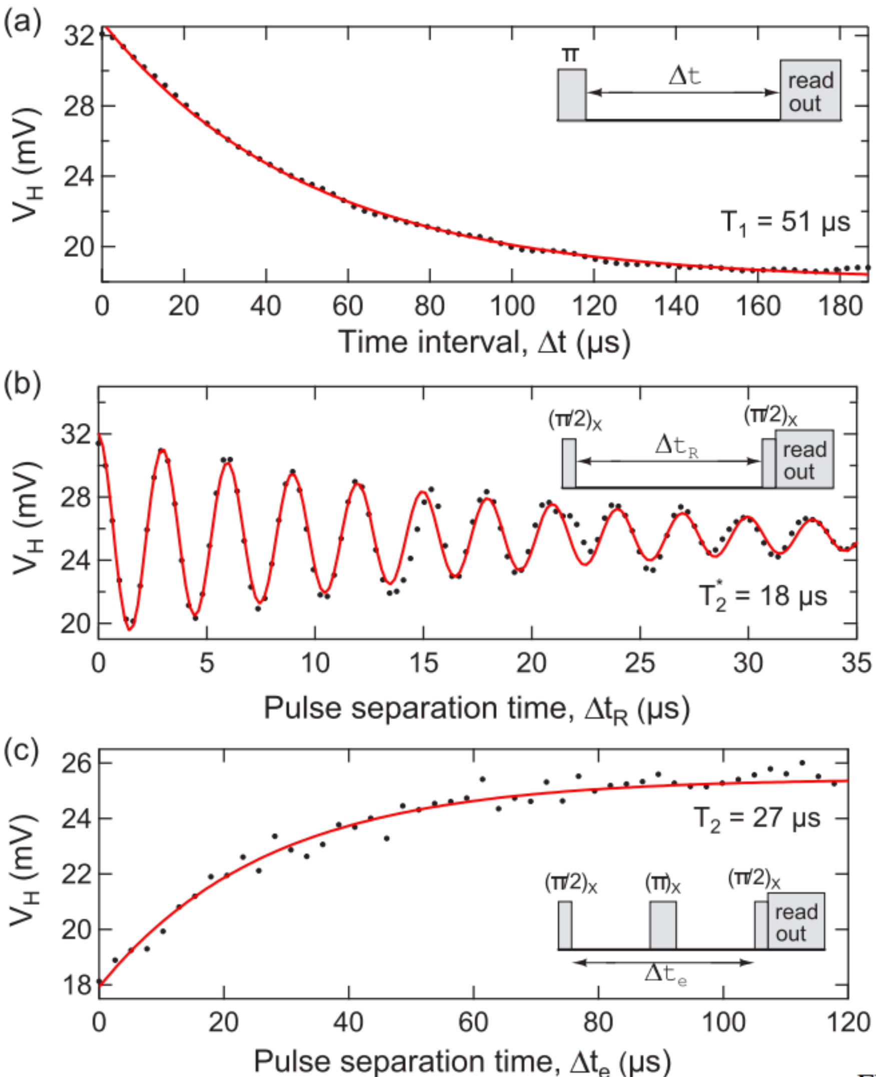

FIG. 4. Time domain measurements of the N7 sample at $B = 7.5$ mG. (a) Relaxation time measurement ($T_1 = 51\ \mu s$). (b) Ramsey fringe experiment ($T_2^* = 18\ \mu s$). (c) Hahn spin echo experiment ($T_2 = 27\ \mu s$). The red solid lines are the fits to the data. See the main text for the fitting functions.

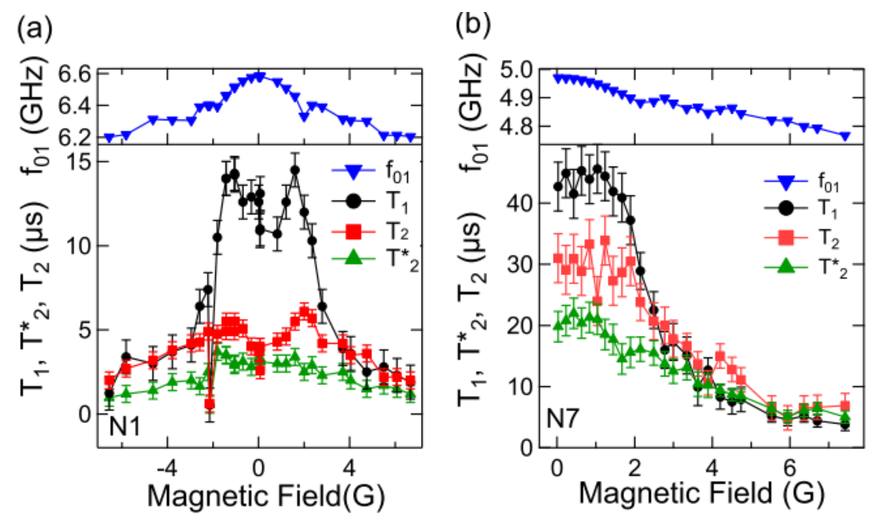

FIG. 6. The qubit transition frequencies (f_{01}) and three times scales (T_1, T_2^*, and T_2) were measured at the sweet spots over the wide range of magnetic field for the N1 (a) and N7 (b).

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Conclusions

- Superconductivity is related to fundamental quantum phenomena. We have revied some of them. They will be discussed in more details in the future lectures.

- Superconductors have been used to create strong and stable magnetic fields, in levitating trains for example.

- Superconducting quantum interference devices enabled researches to measure very small magnetic fields, such as those produced by human brain.

- Superconductors are used to build qubits, which are the building blocks of quantum computers.