Superconductivity in pictures

Alexey Bezryadin

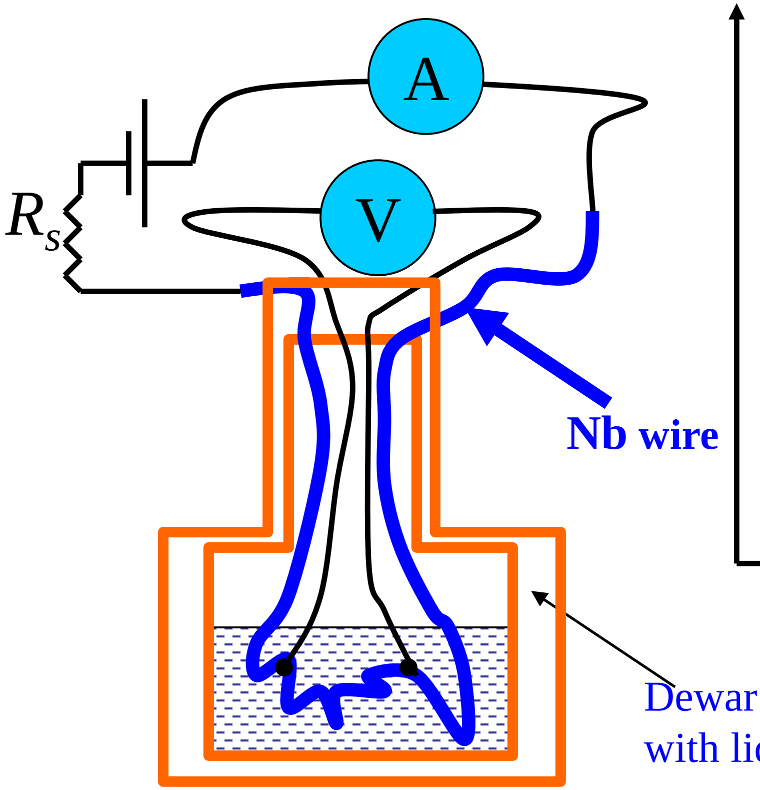
Department of Physics
University of Illinois at Urbana-Champaign

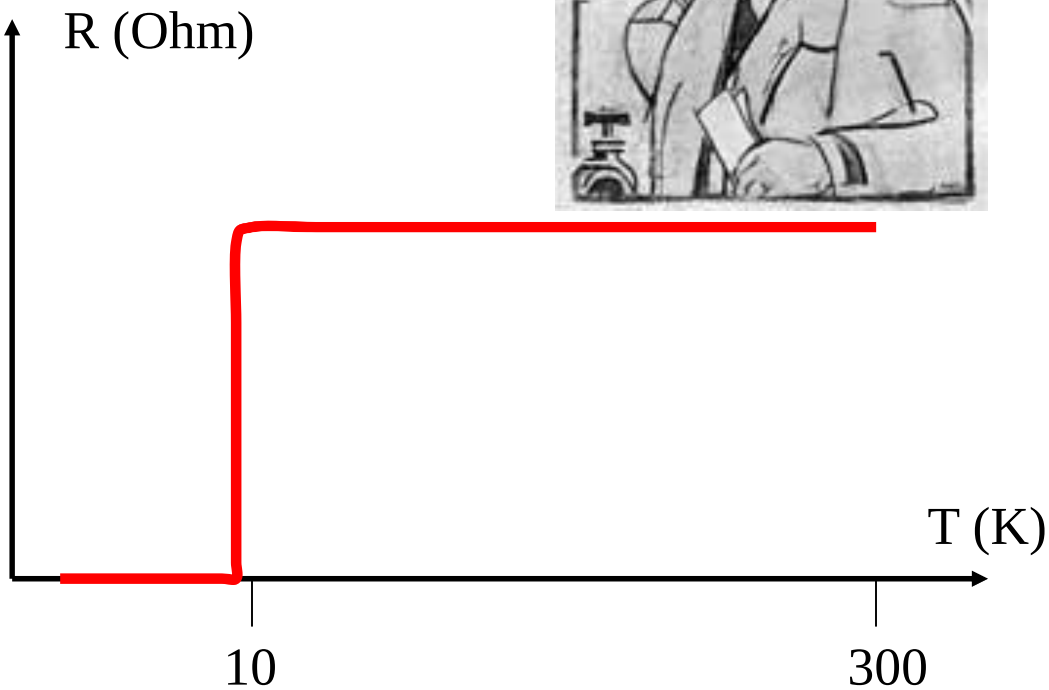
Superconductivity observation

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
- Take Nb wire
- Connect to a voltmeter and a current source
- Put into helium Dewar
- Measure electrical resistance

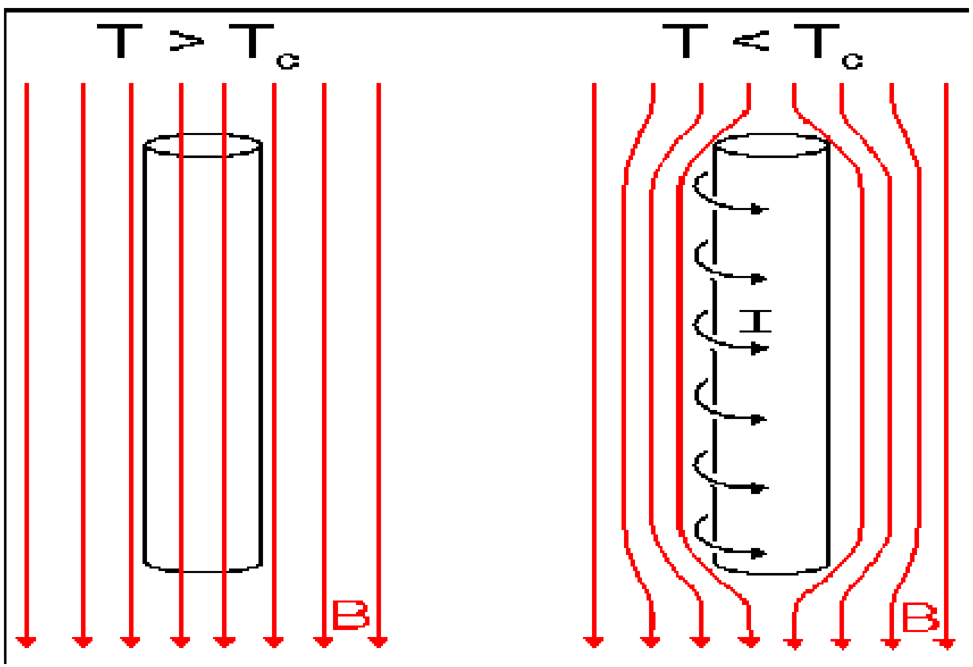
Heike Kamerling Onnes



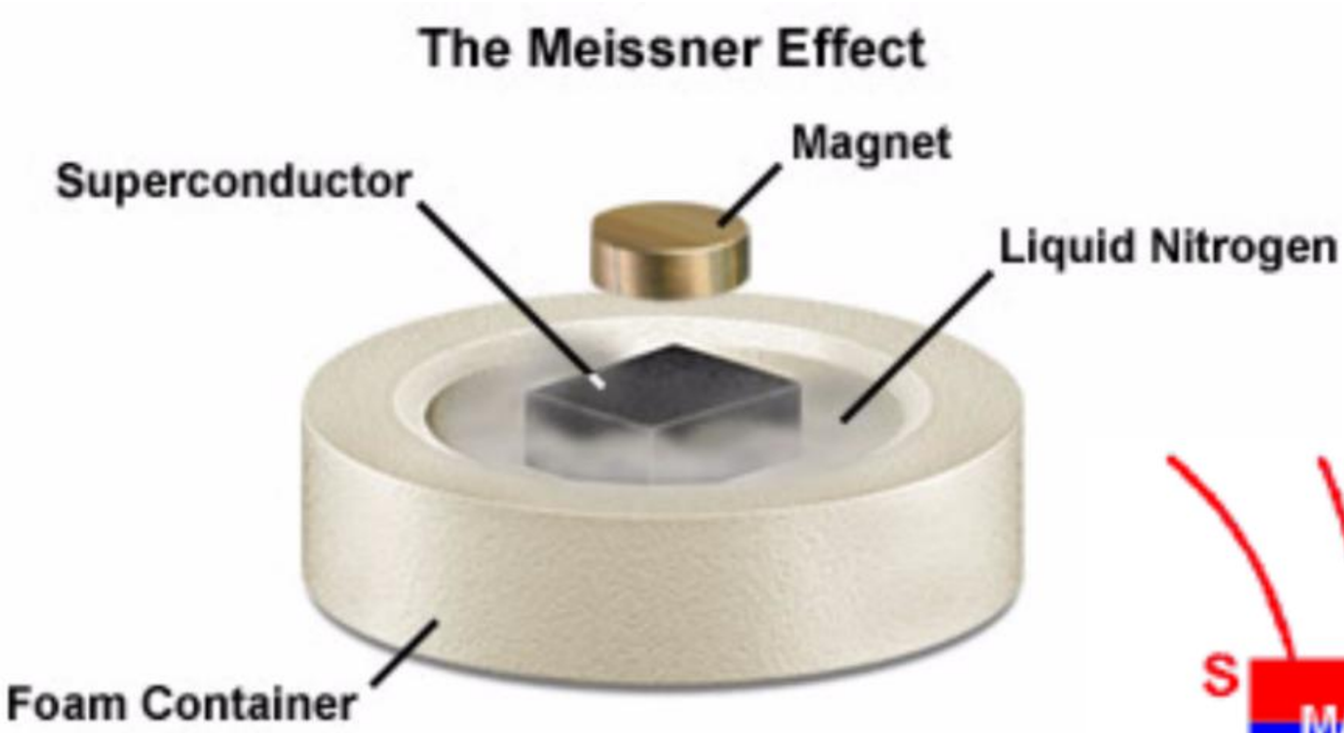


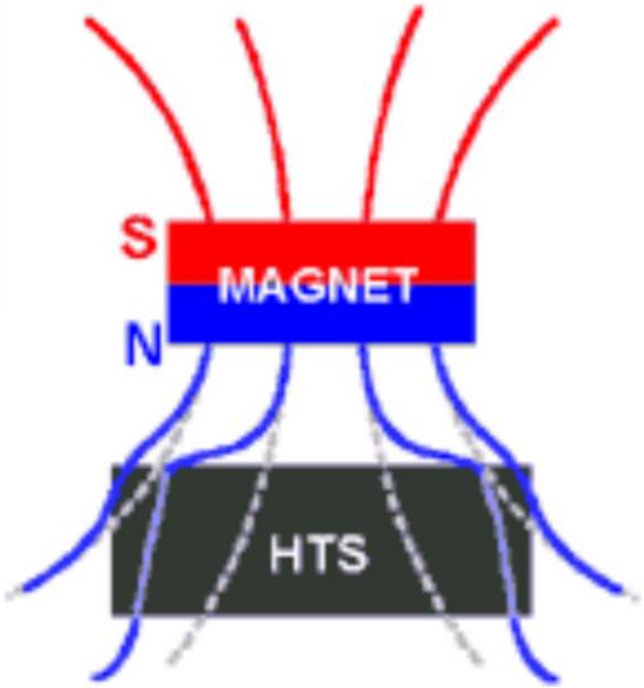
Meissner effect – the key signature of superconductivity

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

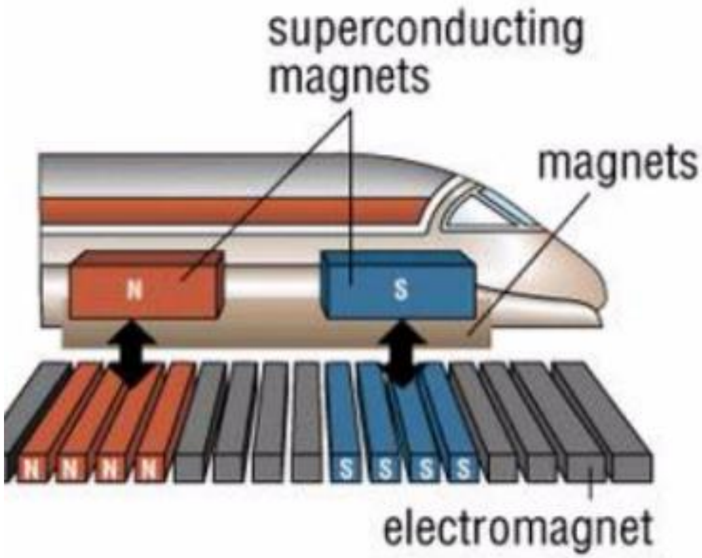


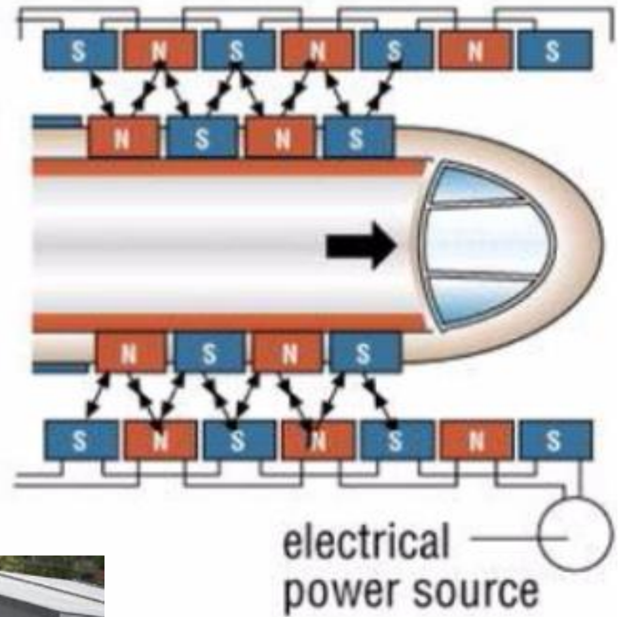
Magnetic levitation





Magnetic levitation train



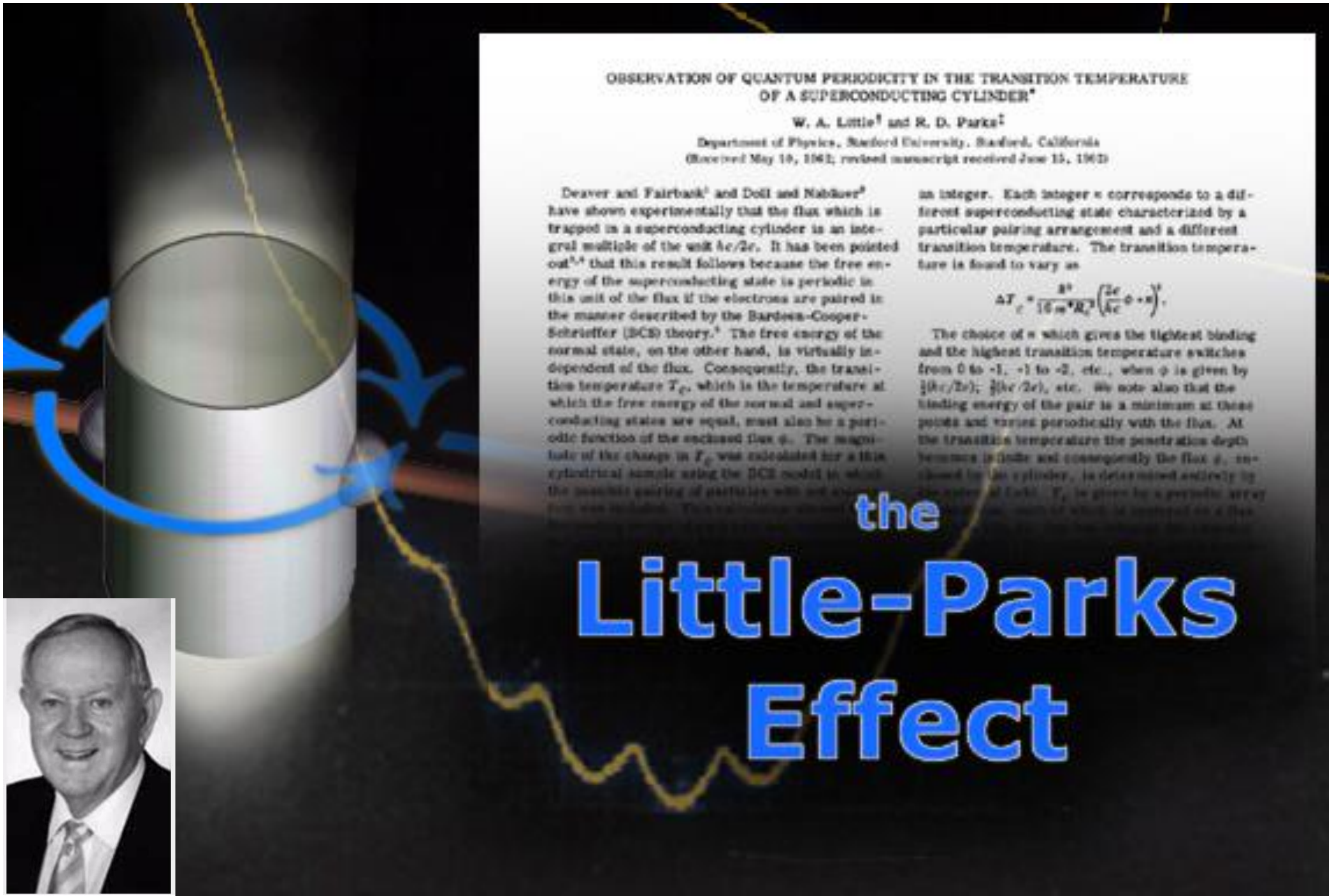


blogs.wsj.com

U.S. Transportation Secretary Foxx Rides on Japan's Maglev Train - Jap...

Searching for an explanation: Little-Parks effect ('62)

The basic idea: magnetic field induces non-zero vector-potential, which produces non-zero superfluid velocity, thus reducing the Tc.

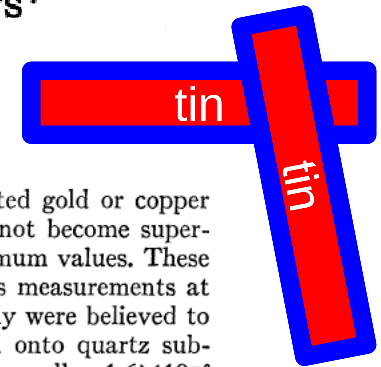


PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Discovery of the supercurrent, known now as proximity effect, in SNS junctions

Superconductivity of Contacts with Interposed Barriers*

Hans Meissner†
Department of Physics, The Johns Hopkins University, Baltimore, Maryland
(Received August 25, 1959)



Resistance *vs* current diagrams and "Diagrams of State" have been obtained for 63 contacts between crossed wires of tin. The wires were plated with various thicknesses of the following metals: copper, silver, gold, chromium, iron, cobalt, nickel, and platinum. The contacts became superconducting, or showed a noticeable decrease of their resistance at lower temperatures if the plated films were not too thick. The limiting thicknesses were about 35×10^{-6} cm for Cu, Ag, and Au; 7.5×10^{-6} cm for Pt, 4×10^{-6} cm for Cr, and less than 2×10^{-6} cm for the ferromagnetic metals Fe, Co, and Ni. The investigation was extended to measurements of the resistance of contacts between crossed wires of copper or gold plated with various thicknesses of tin. Simultaneous measurements of the (longitudinal) resistance of the tin-plated gold or copper wires showed that these thin films of tin do not become superconducting for thicknesses below certain minimum values. These latter findings are in agreement with previous measurements at Toronto. The measurements at Toronto usually were believed to be unreliable because films of tin evaporated onto quartz substrates can be superconducting at thicknesses as small as 1.6×10^{-6} cm. It is now believed that just as superconducting electrons can drift into an adjoining normal conducting layer and make it superconducting, normal electrons can drift into an adjoining superconducting layer and prevent superconductivity.

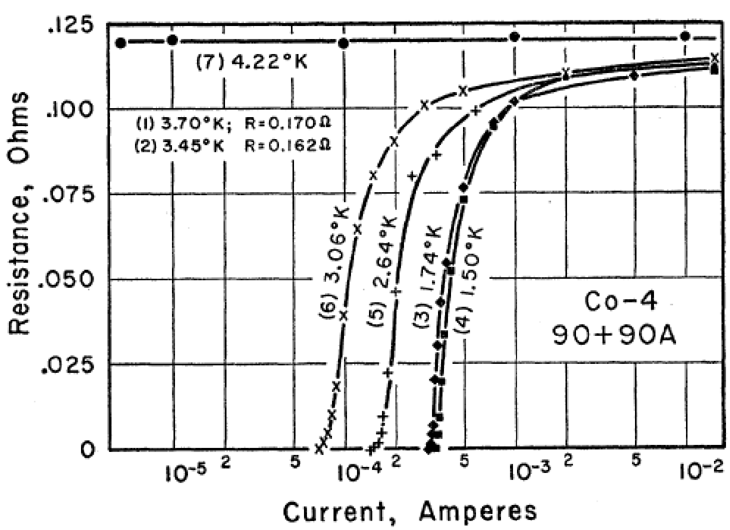


FIG. 1. Resistance *vs* current diagram of cobalt-plated contact Co 4, representative of diagrams type A.

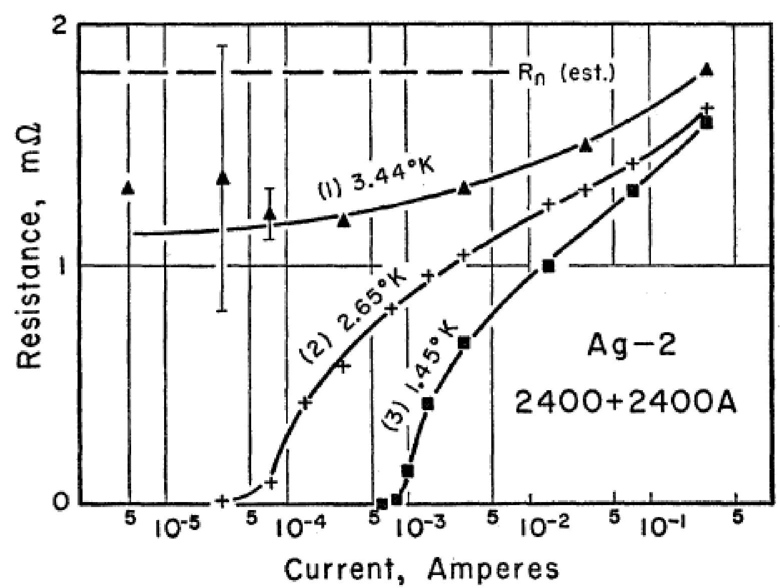
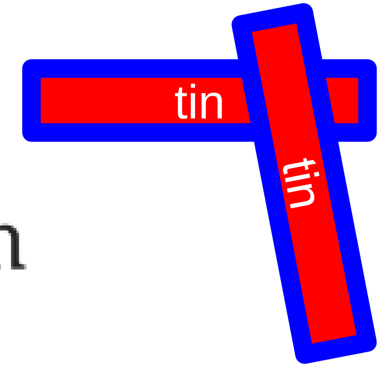
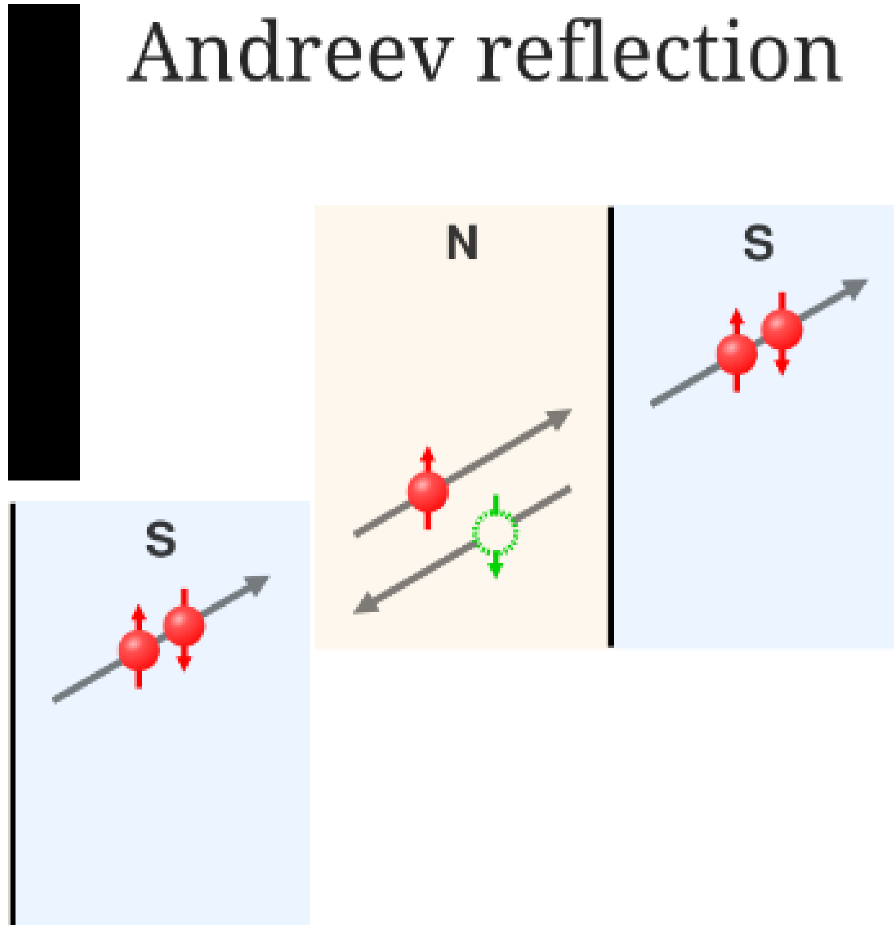


FIG. 2. Resistance *vs* current diagram of silver-plated contact Ag 2, representative of diagrams type B.

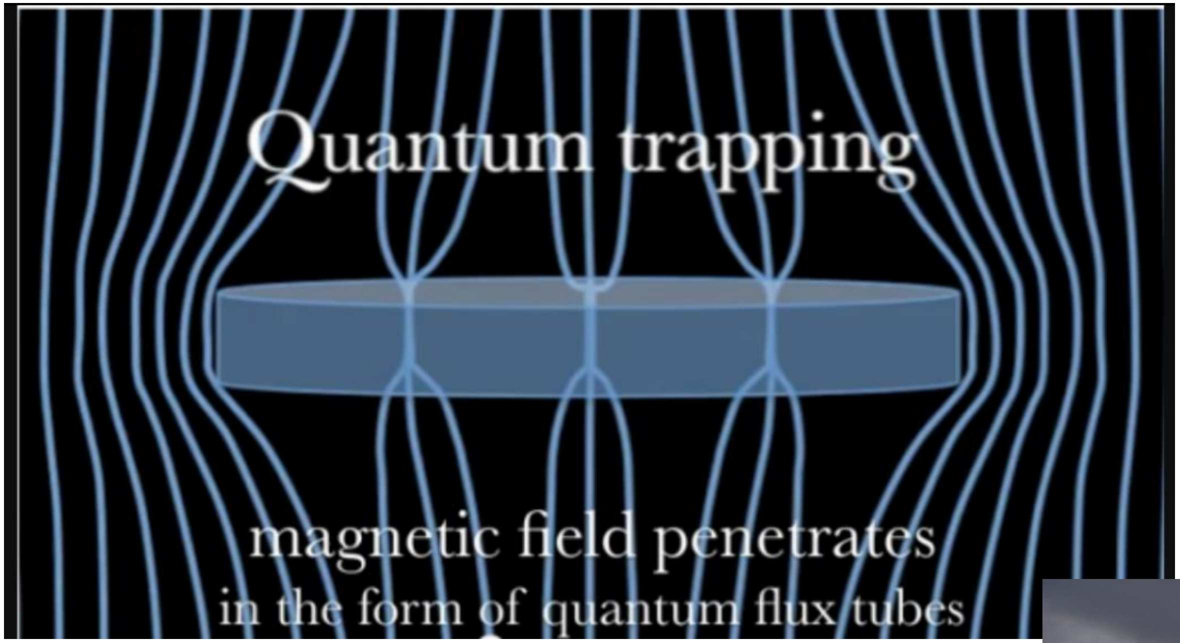
Explanation of the supercurrent in SNS junctions --- Andreev reflection





A.F. Andreev 1964

Superconducting vortices produced by magnetic field



Superconductivity in thin films (2D)

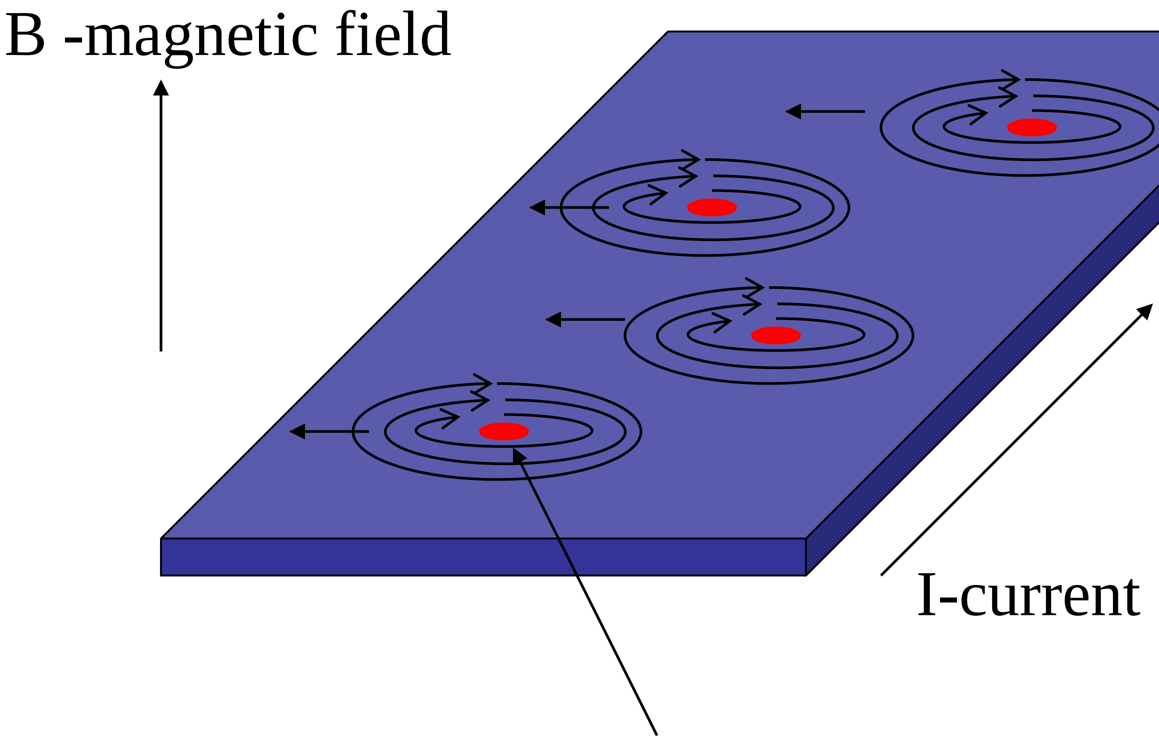
Magnetic field creates vortices--

Vortices cause dissipation (i.e. a non-zero electrical resistance)!

$2eV = \hbar\, d\varphi/dt$

φ changes by 2π

As one quantum vortex crosses the superconducting film



The order parameter:

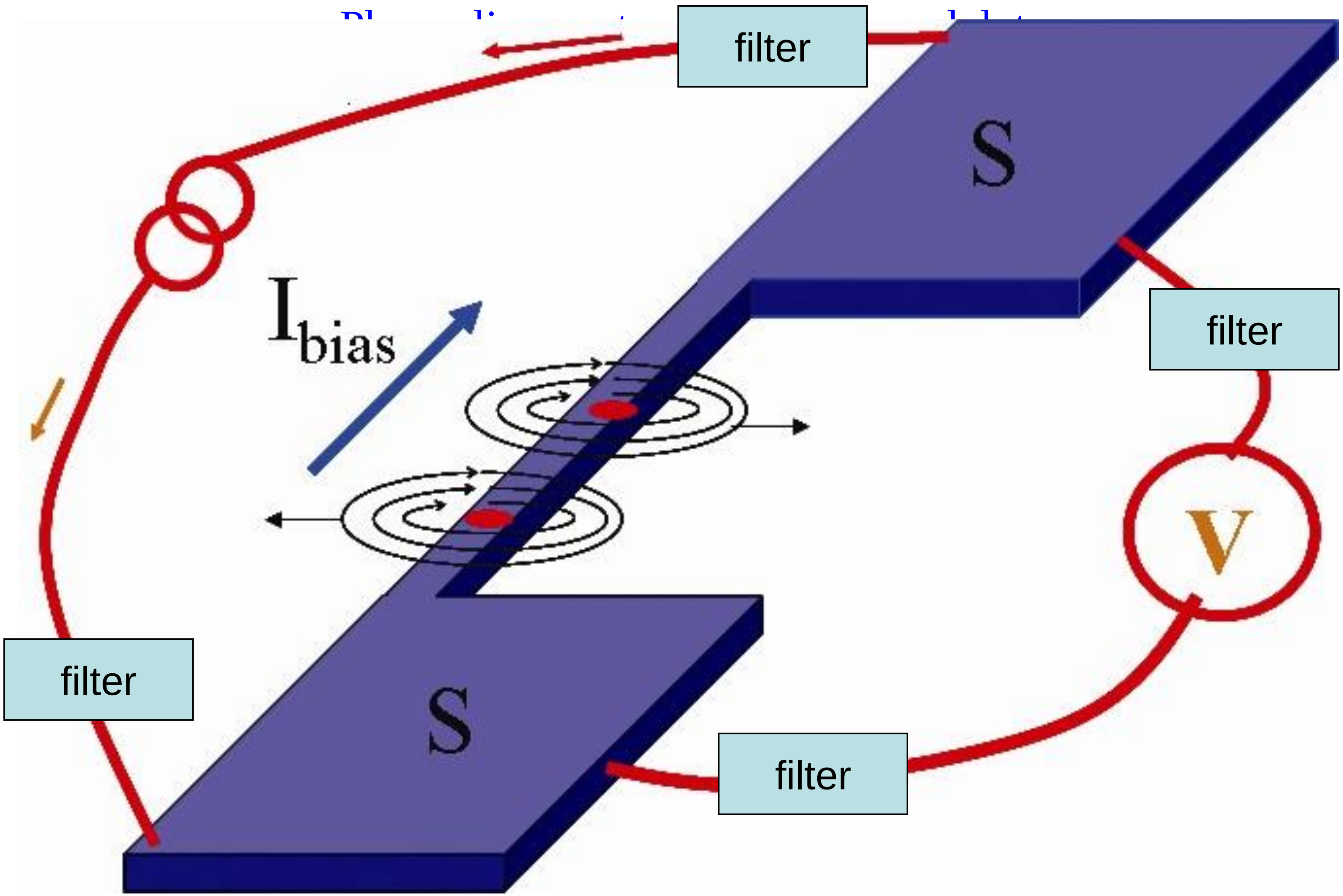
$$\Psi = |\Psi| \exp(-i\varphi)$$

amplitude

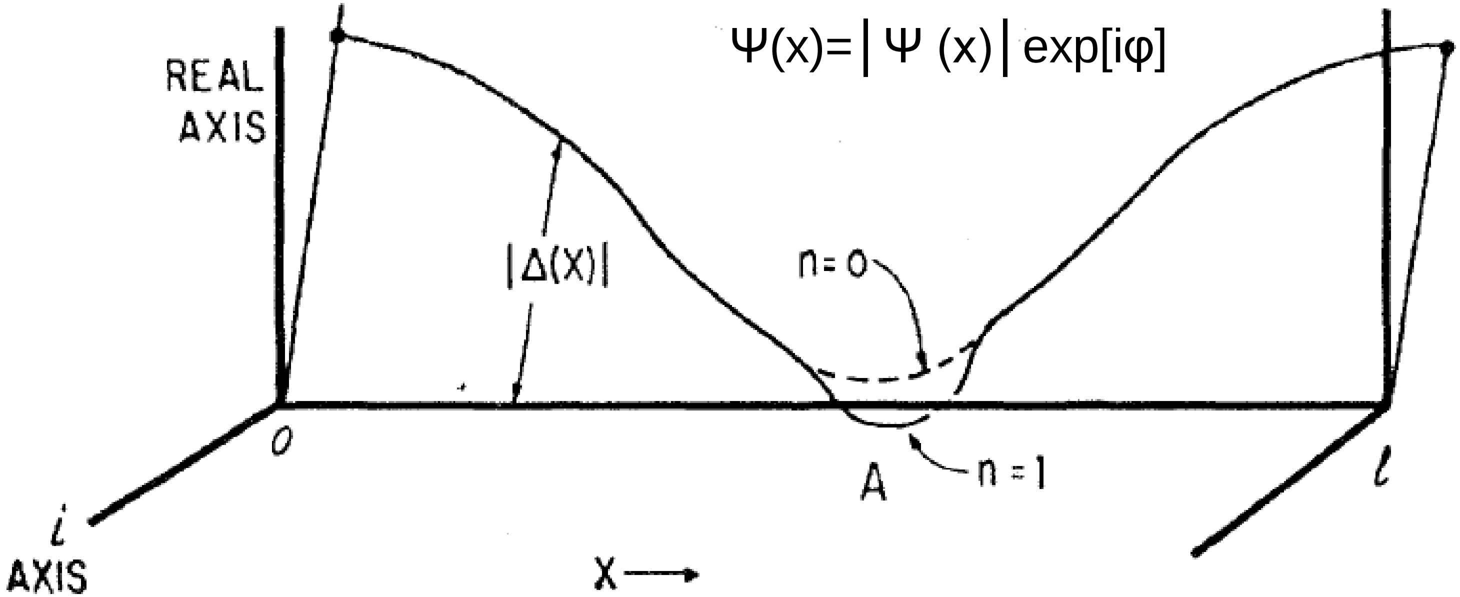
phase

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

DC transport measurement in one dimensional (1D) superconducting wires



Transport properties: Little's Phase Slip



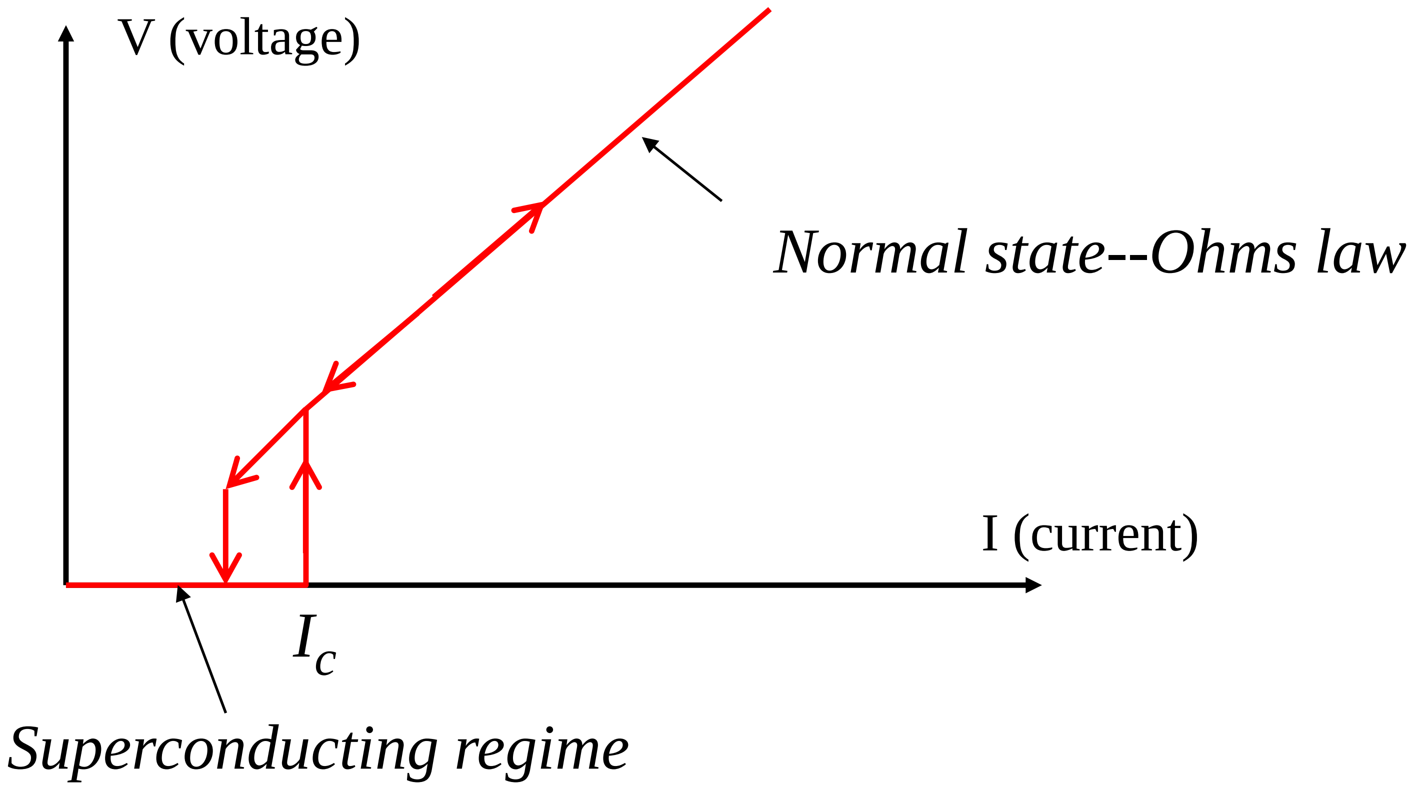
W. A. Little, "Decay of persistent currents in small superconductors", Physical Review, V.156, pp.396-403 (1967).

Two types of phase slips (PS) can be expected:

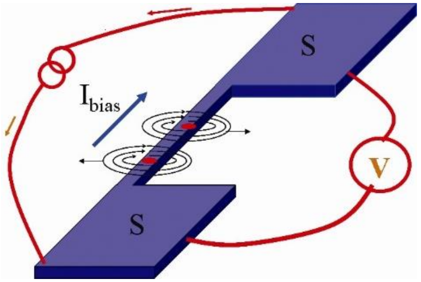
1. The usual, thermally activated PS (TAPS)
2. Quantum phase slip (QPS)

Superconductivity: very basic introduction

Electrical resistance is zero only if current is not too strong



How to use voltage to figure out the rate of phase slips?



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

$2eV = \hbar \, d\varphi/dt$

Remember Shrodingerequation:

$i \hbar (d\Psi/dt) = E \Psi$

Therefore, $\varphi = Et/\hbar$

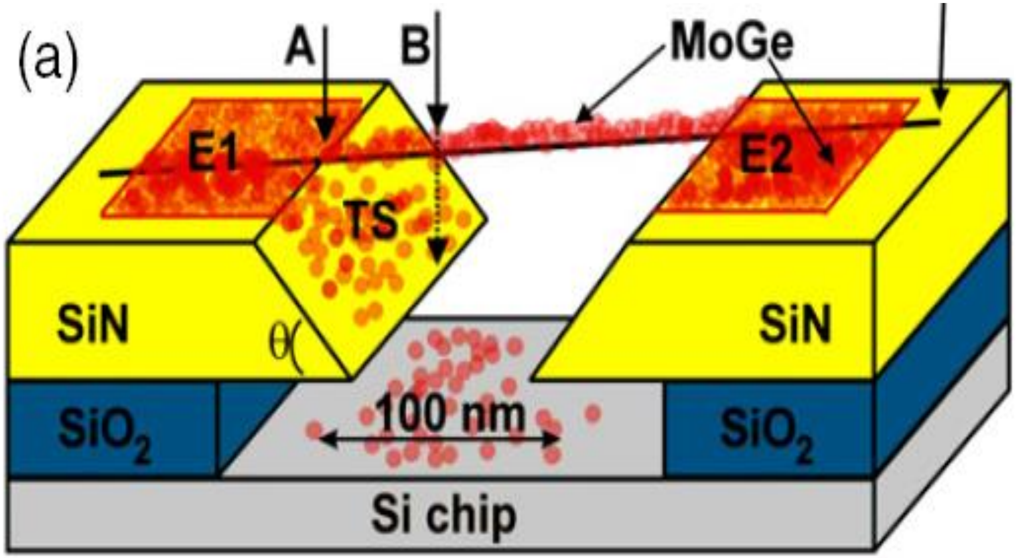
But for BCS pairs $E=2eV$,

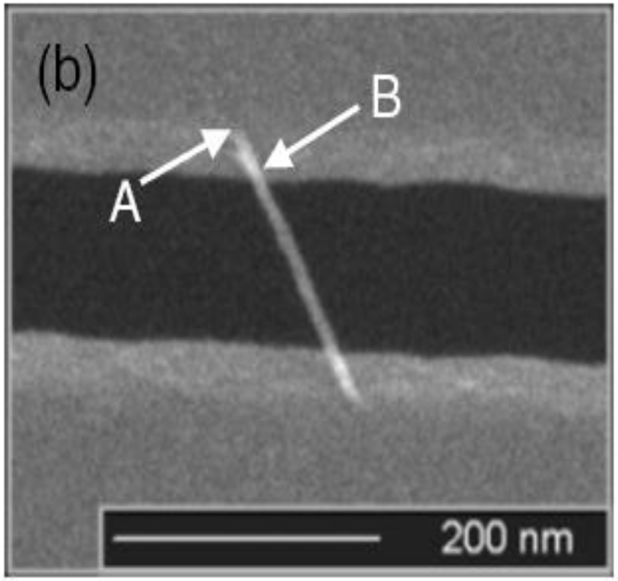
where V is the electric potential.

Thus the equation above can be obtained.

Fabrication of nanowires

Method of Molecular Templating





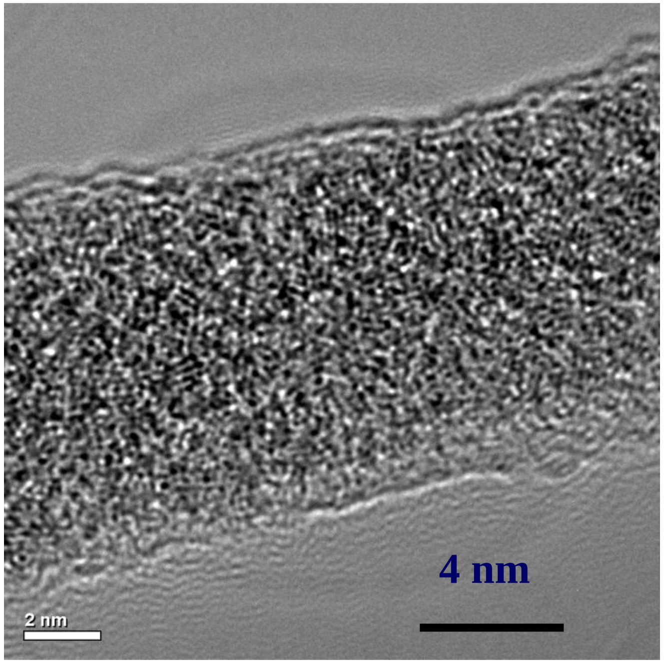
Si/ SiO_2/SiN substrate with undercut

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

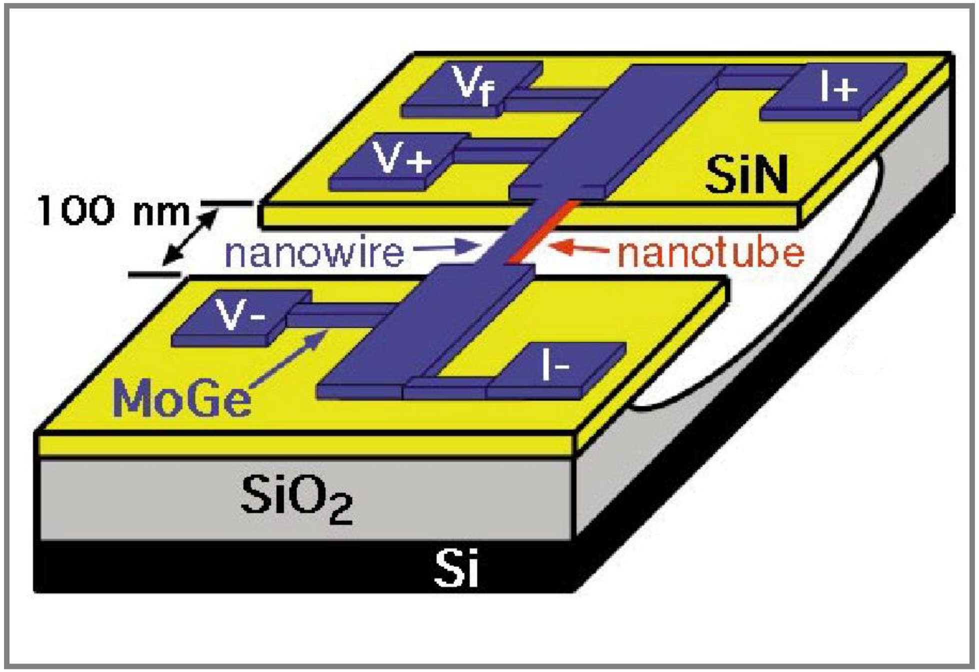
HF wet etch for ~10 seconds to form undercut

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

Sample Fabrication

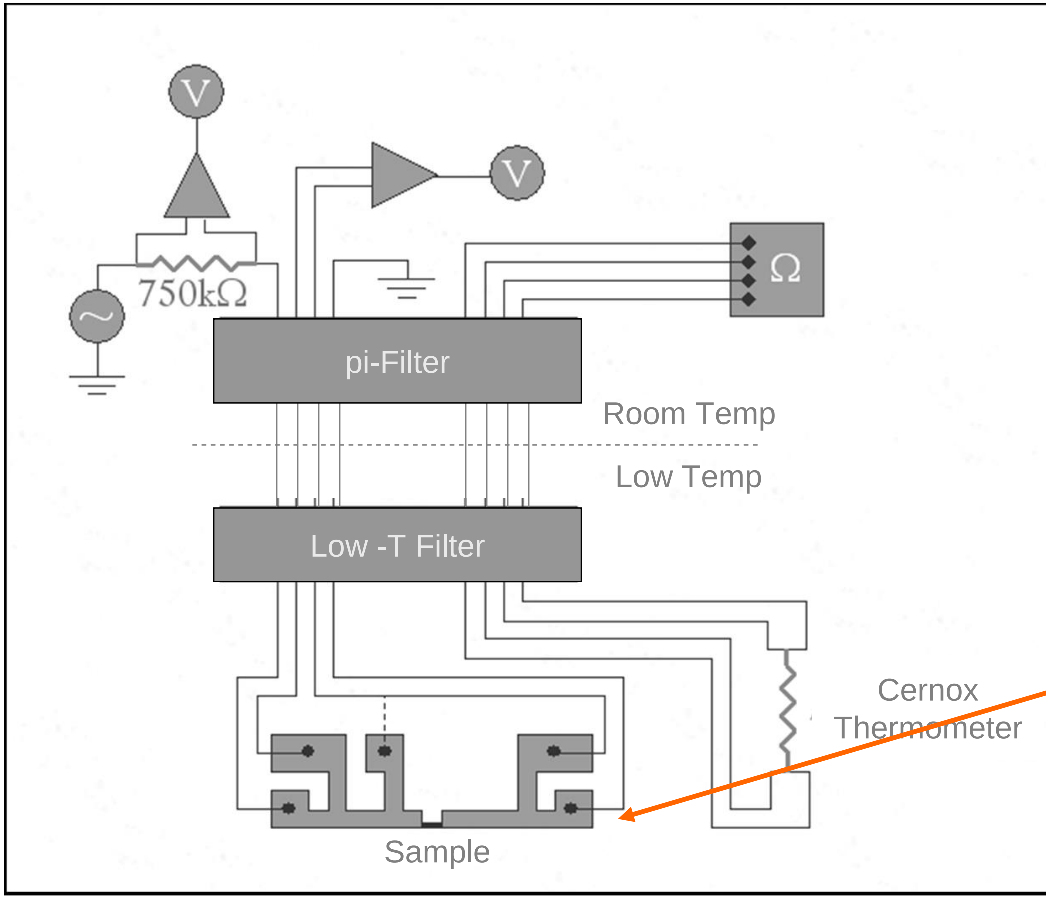


TEM image of a wire shows amorphous morphology.
Nominal MoGe thickness = 3 nm

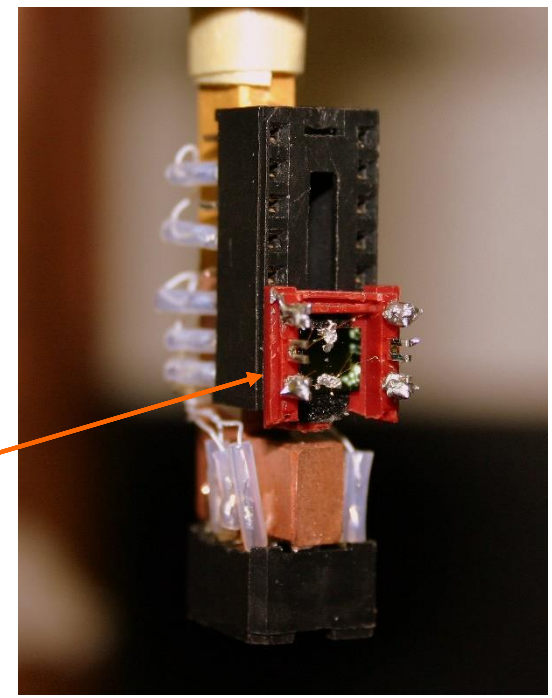


Schematic picture of the pattern
Nanowire + Film Electrodes used in
transport measurements

Measurement Scheme



Circuit Diagram



Sample mounted on the ^{3}He insert.

Tony Bollinger's sample-mounting procedure in winter in Urbana

Procedure (~75% Success)

- Put on gloves

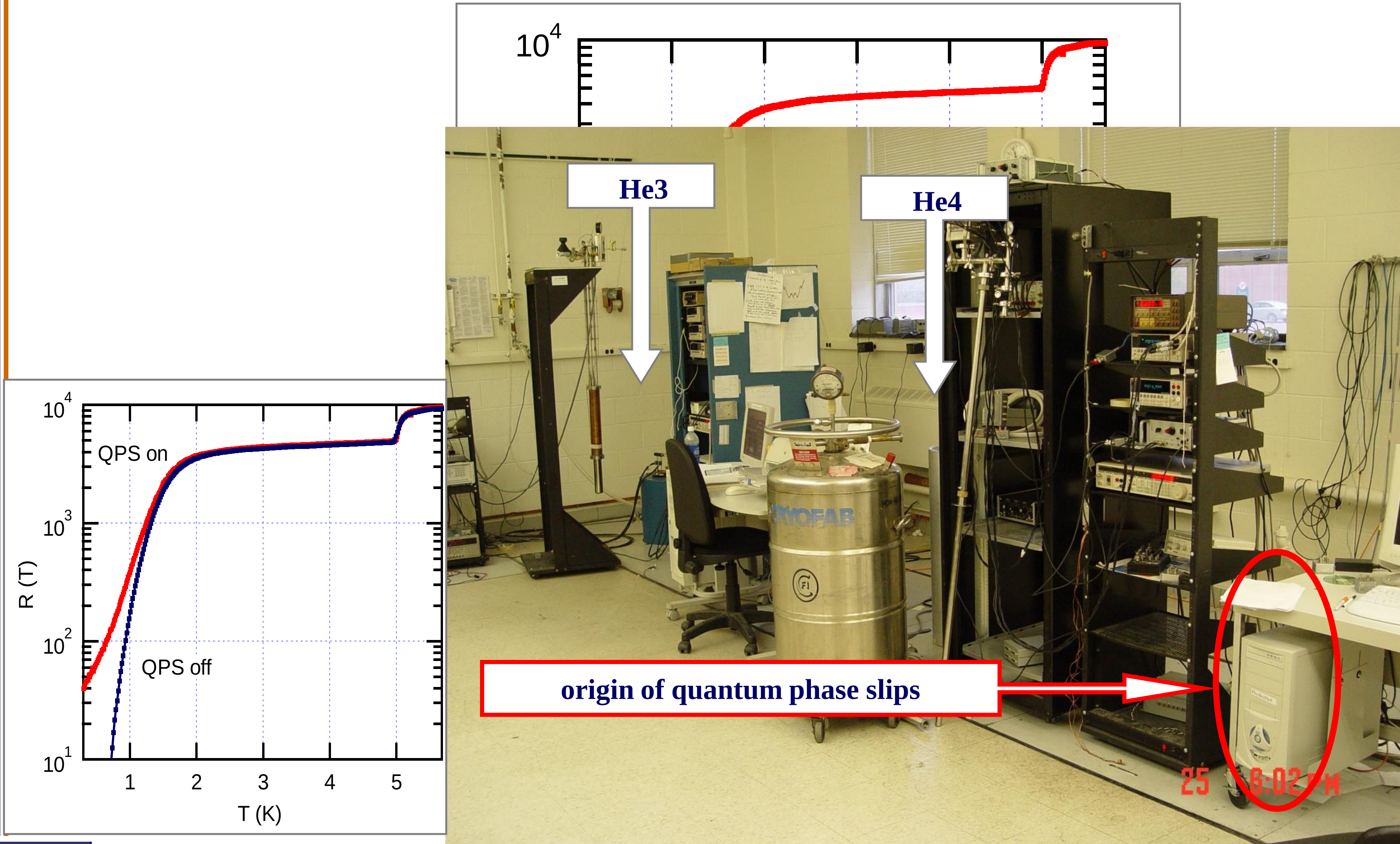
- Put grounded socket for mounting in vise with grounded indium dot tool connected
- Spray high-backed black chair all over and about 1 m square meter of ground with anti-static spray

    - DO NOT use green chair
    - Not sure about short-backed black chairs

- Sit down
- Spray bottom of feet with anti-static spray

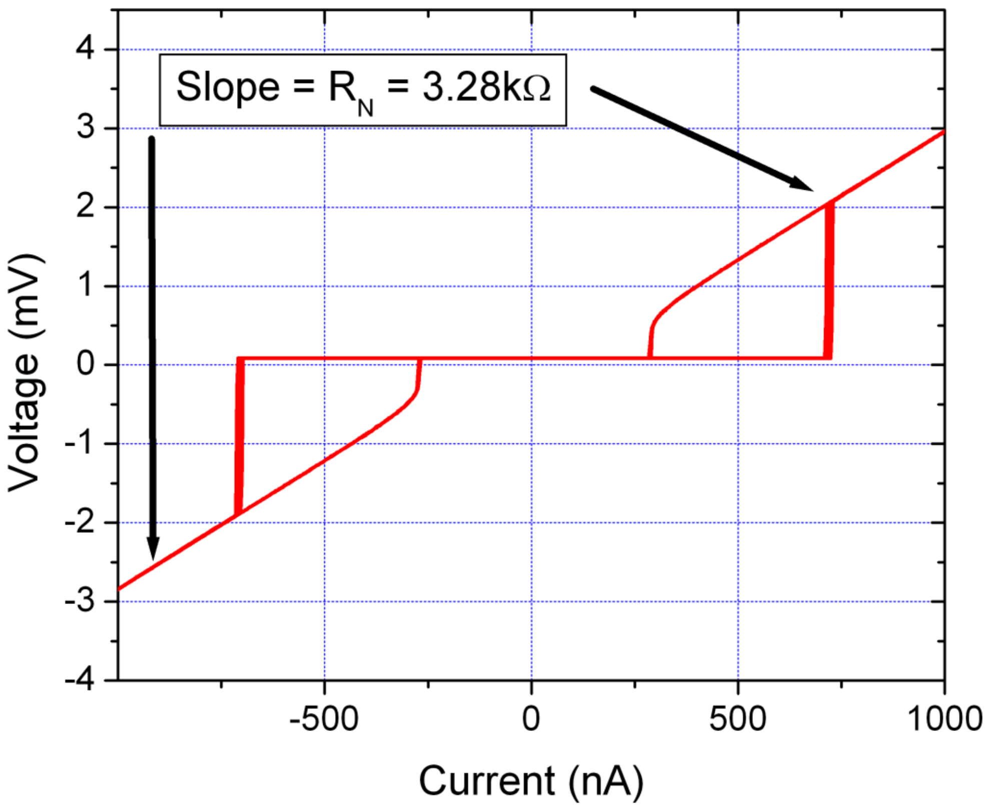
- Plant feet on the ground. ***Do not move your feet again for any reason until mounting is finished.***
- Mount sample
- Keep sample in grounded socket until last possible moment
- Test samples in dipstick at ~1 nA

Possible Origin of Quantum Phase Slips



Dell is good

Search for QPS at high bias currents, by measuring the fluctuations of the switching current



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

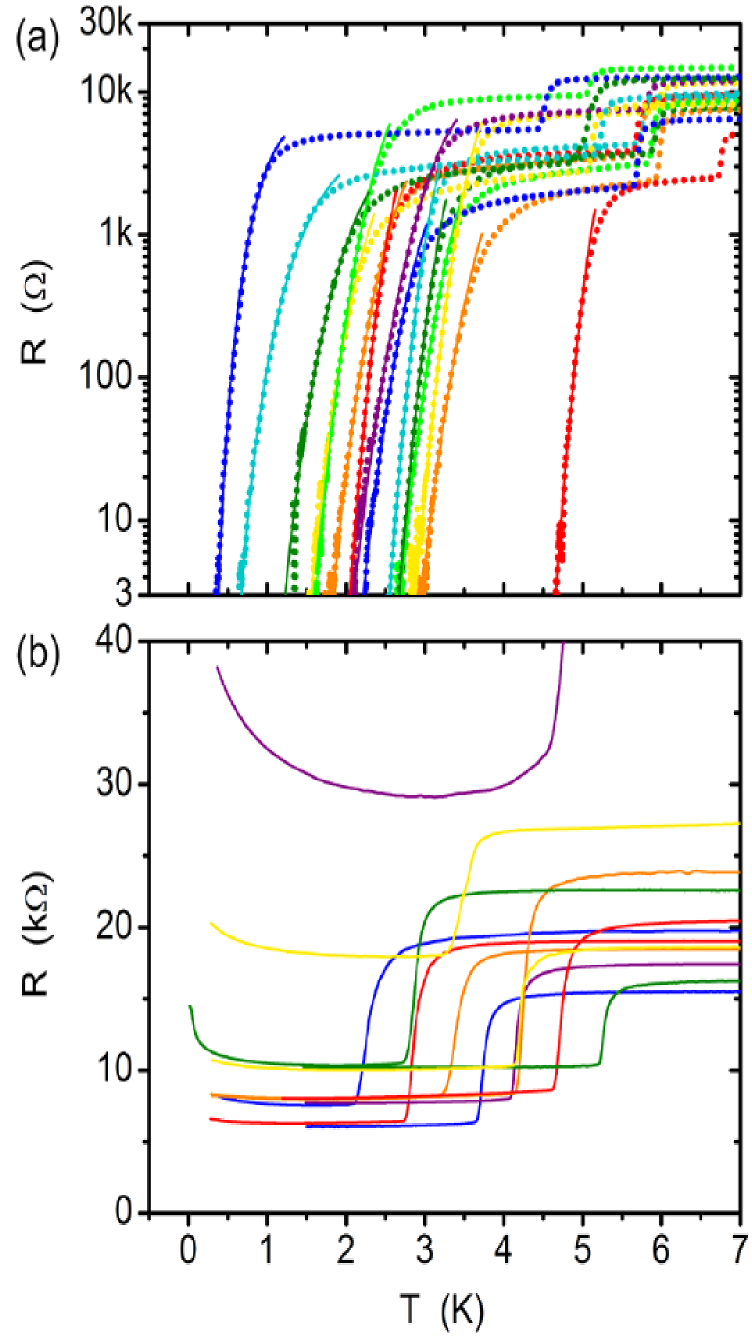
R=V/I   I~3 nA

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

The threshold for superconductivity in thin wires is the quantum resistance:

$$R_Q = h / 2e^2 = 6.5\ \text{k}\Omega$$

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



Useful Expression for the Free Energy of a Phase Slip

"Arrhenius-Little" formula for the wire resistance:

$$R_{AL} \approx R_N \, exp[-\Delta F(T)/k_B T]$$

$$\Delta F = (8\sqrt{2}/3)(H_c(T)^2/8\pi)(A\xi(T))$$

$$\frac{\Delta F(0)}{k_B T_c} = \sqrt{6}\,\frac{\hbar I_c(0)}{2ek_B T_c} = 0.83\,\frac{R_q L}{R_n \xi(0)} = 0.83\,\frac{R_q}{R_{\xi(0)}}$$

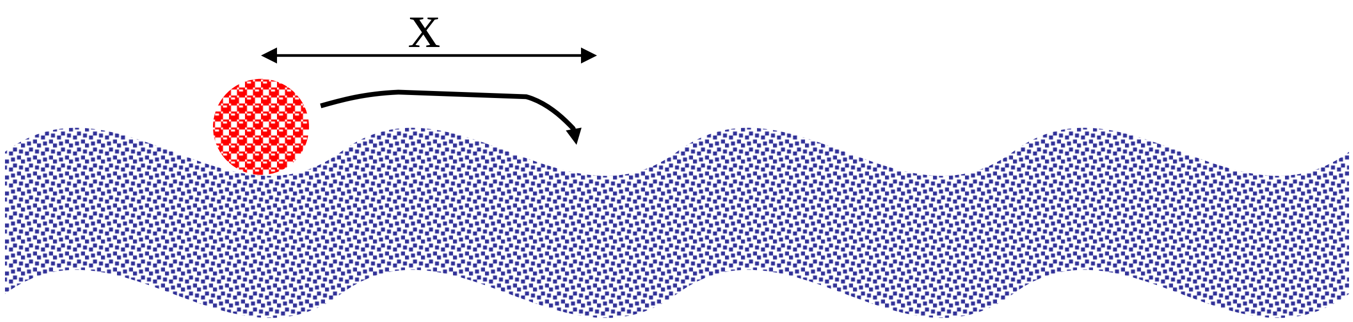
APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 16 22 APRIL 2002

Quantum limit to phase coherence in thin superconducting wires

M. Tinkham[a)] and C. N. Lau
Physics Department, Harvard University, Cambridge, Massachusetts 02138

Schmid transition. Basic idea – localization by dissipation.

The friction force is $F_{fr} = \eta v$, where η is the classical damping coefficient



Tunneling in periodic potential in the presence of dissipation

Caldeira and Leggett, *Phys. Rev. Lett.*, 46, 211 (1980)

<u>"Derivation" of the critical damping coefficient:</u>

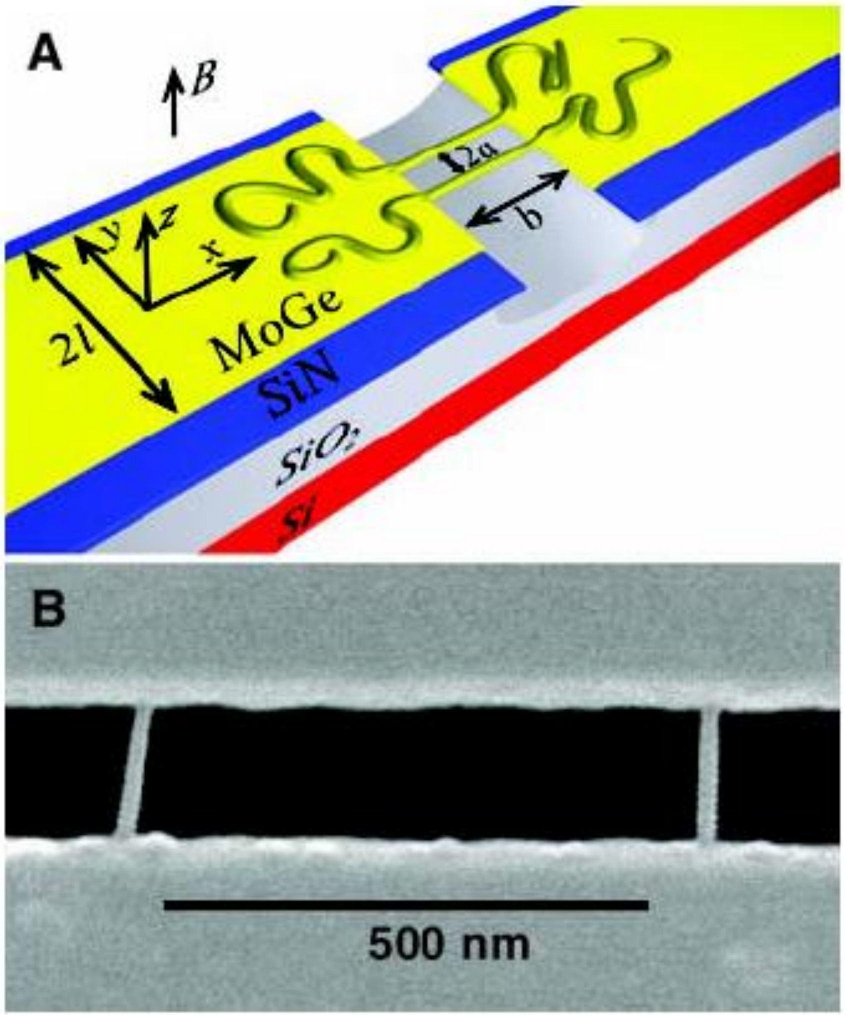
$px \sim \hbar/2$; $v \sim \hbar/2mx$; $F_{fr} = \eta v = \eta\, \hbar/2mx$; $W_{fr} = \eta v x = \eta\, \hbar/2m$

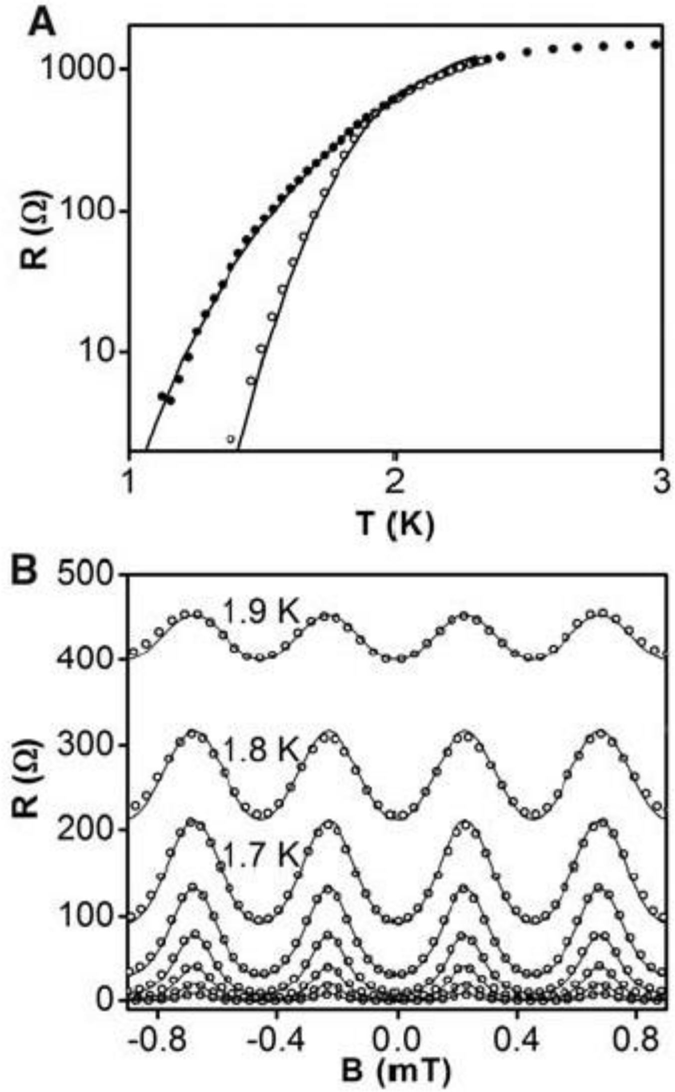
The particle <u>can not tunnel</u> if $W_{fr} > p^2/2m$ or $\eta\, \hbar/2m > (1/2m)\, (\hbar/x)^2$

So tunneling is blocked if **$\eta > \hbar/x^2$** **(exact result: $\eta > h/x^2$)**

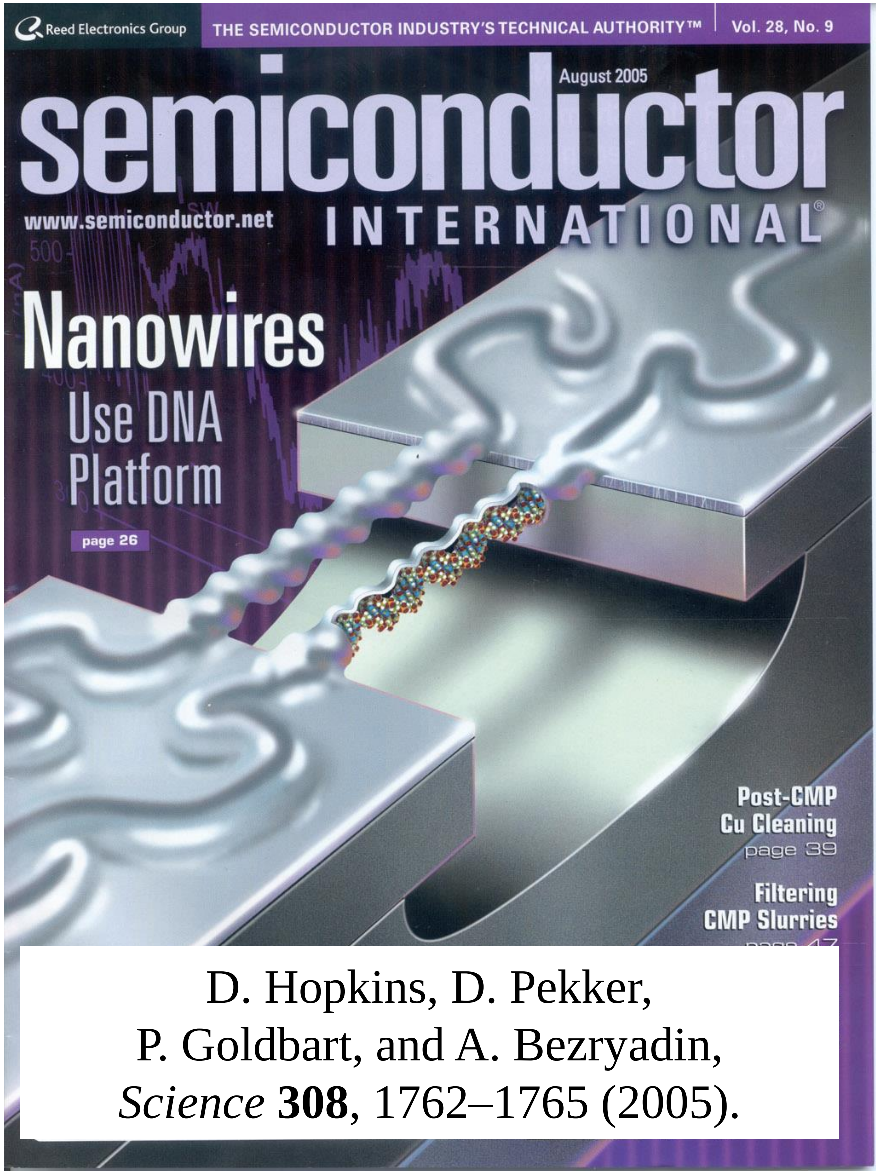
What determines the period of oscillation?

(A simple guess for the period would be $\Delta B \sim \Phi_0/2ab$.
This prediction deviates from the result by a factor 100!)

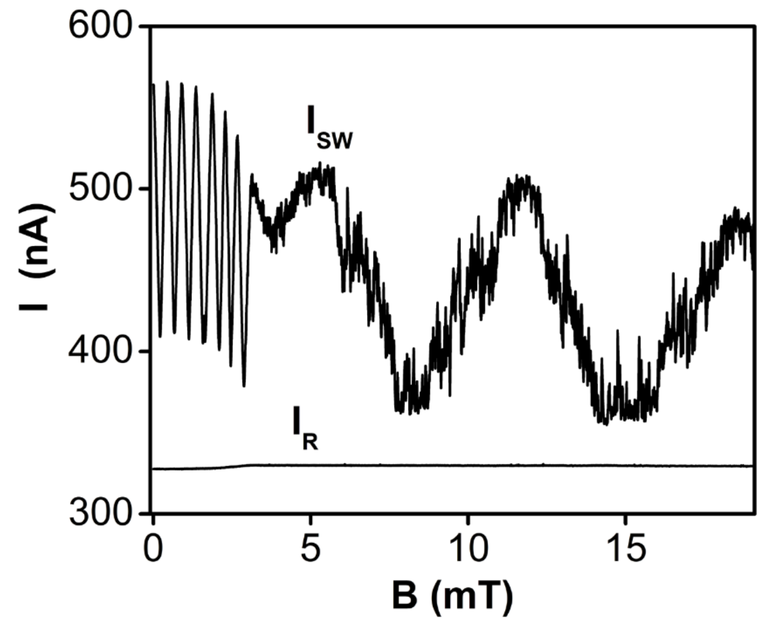


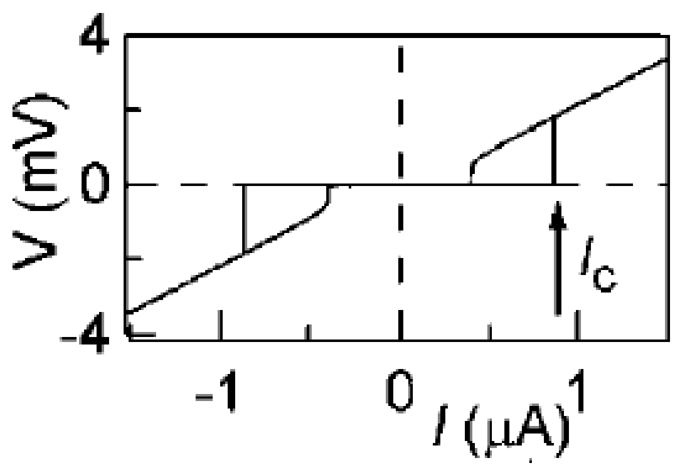


Phase gradiometers templated by DNA

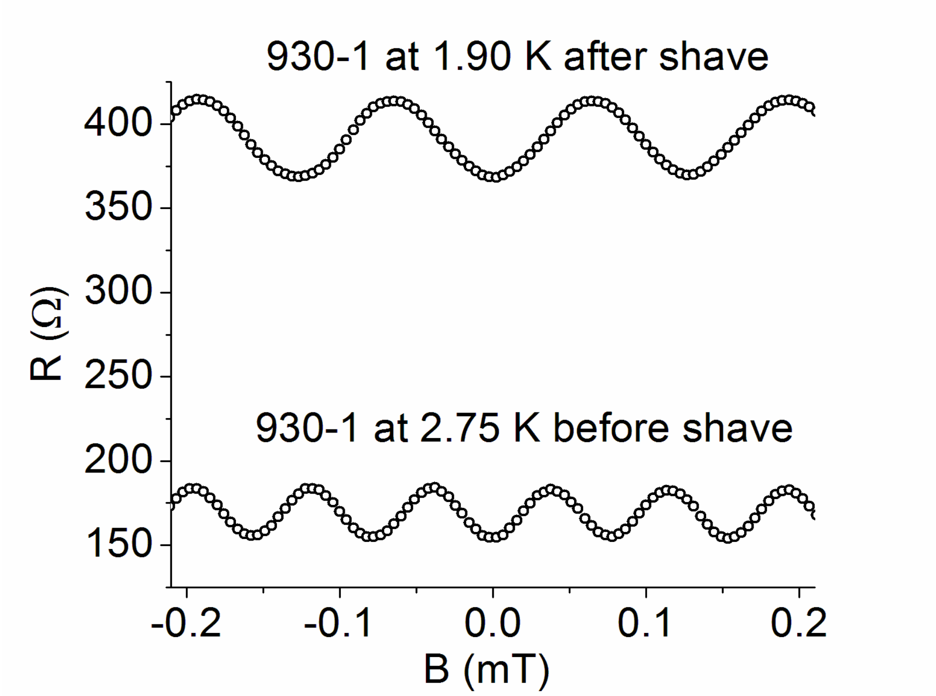


D. Hopkins, D. Pekker,
P. Goldbart, and A. Bezryadin,
Science **308**, 1762–1765 (2005).



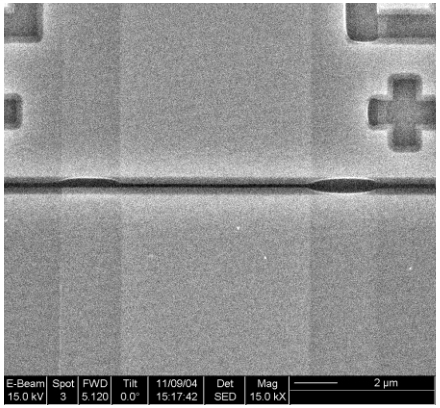


Little-Parks effect.
The period of the oscillation is inversely proportional to the width of the electrodes



The width of the leads was changed from 14480 nm to 8930 nm

The period changed from 77.5 μT to 128 μT



usual SQUID estimate:

$$Period = \frac{\Phi_0}{2ab} \sim 10mT$$

here *2a*-distance between the wires;

b- length of wires

Correct field period:

$$\Delta B = \frac{\pi^2 \Phi_0}{8G\,4al}$$

here *2l* - the width of the leads

G = .916 is the Catalan number

SQUID – superconducting quantum interference device

SQUID helmet project at Los Alamos

Magnetic field scales:

Earth field: ~1G

Fields inside animals: ~0.01G-0.00001G

Fields on the **human brain**: ~0.3nG
This is less than a hundred-millionth of the Earth's magnetic field.

SQUIDs, or Superconducting Quantum Interference Devices, invented in 1964 by Robert Jaklevic, John Lambe, Arnold Silver, and James Mercereau of Ford Scientific Laboratories, are used to measure extremely small magnetic fields. They are currently the most sensitive magnetometers known, with the noise level as low as 3 $fT \cdot Hz^{-1/2}$. While, for example, the Earth magnet field is only about 0.0001 Tesla, some electrical processes in animals produce very small magnetic fields, typically between 0.000001 Tesla and 0.000000001 Tesla. SQUIDs are especially well suited for studying magnetic fields this small.
Measuring the brain's magnetic fields is even much more difficult because just above the skull the strength of the magnetic field is only about 0.3 picoTesla (0.0000000000003 Tesla). This is less than a hundred-millionth of Earth's magnetic field. In fact, brain fields can be measured only with the most sensitive magnetic-field sensor, i.e. with the superconducting quantum interference device, or SQUID.

Linearity of the Schrödinger's equation

Suppose Ψ_1 is a valid solution of the Schrödinger equation:

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

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

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

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

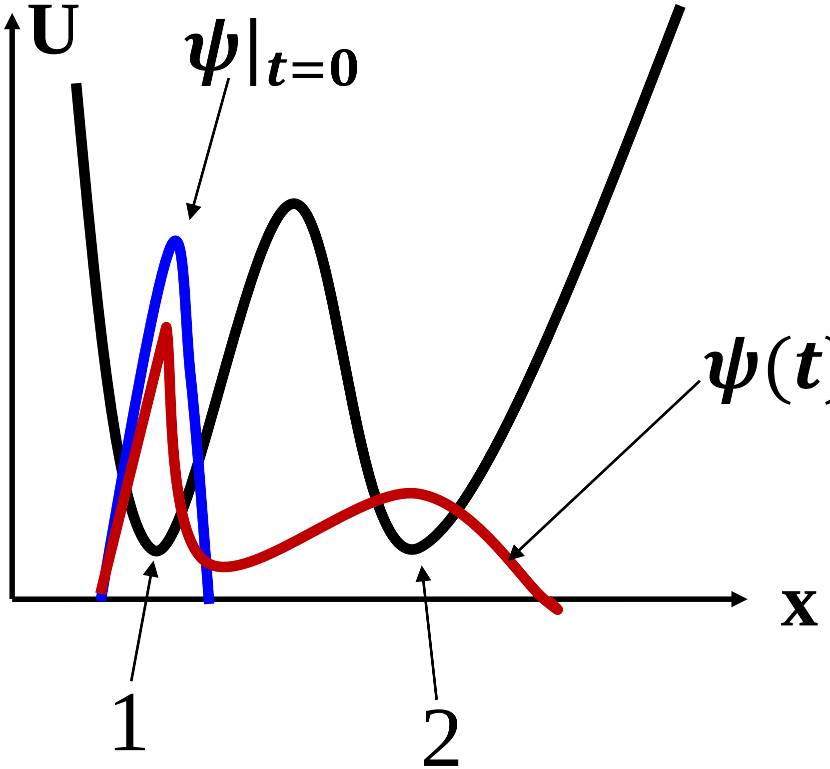
$$i\hbar\frac{\partial(\psi_1+\psi_2)}{\partial t}=\frac{\partial^2(\psi_1+\psi_2)}{\partial x^2}+U(x)(\psi_1+\psi_2)$$

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

Quantum tunneling

George Gamow

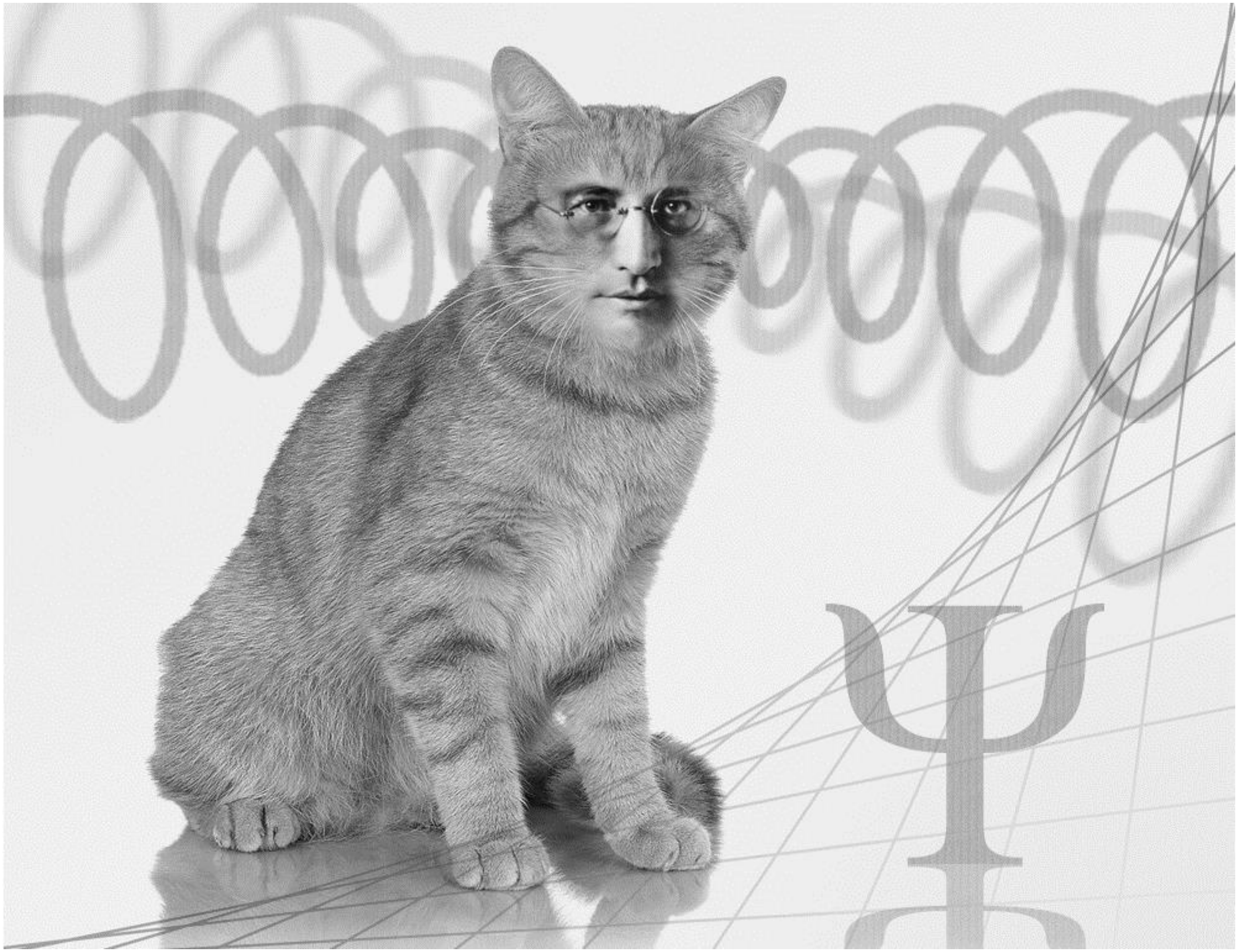
(He also developed Big Bang theory)



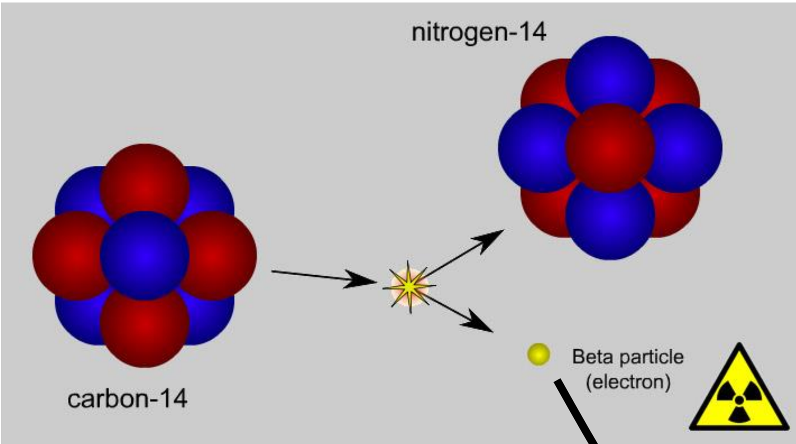
Quantum tunneling is possible since quantum superpositions of states are possible.

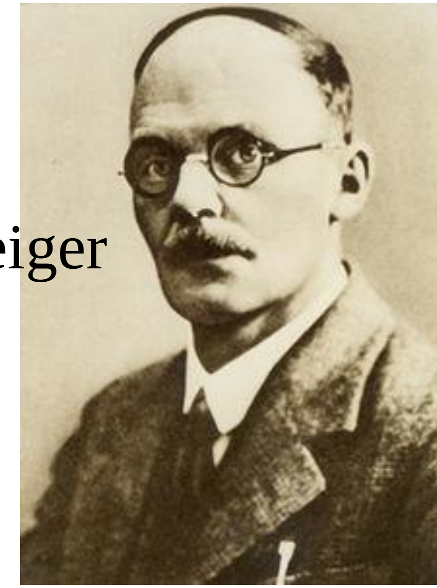
Schrödinger cat –
the ultimate macroscopic quantum phenomenon

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



Schrödinger cat – thought experiment

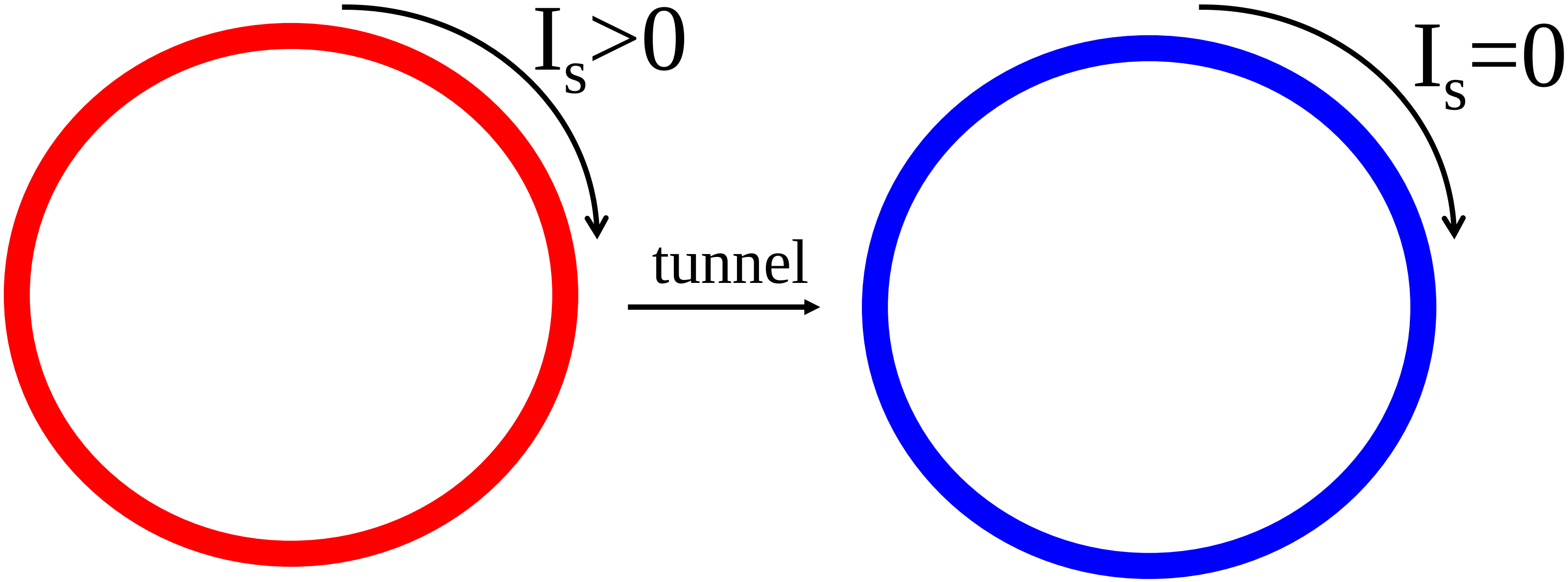




Hans Geiger

Geiger counter

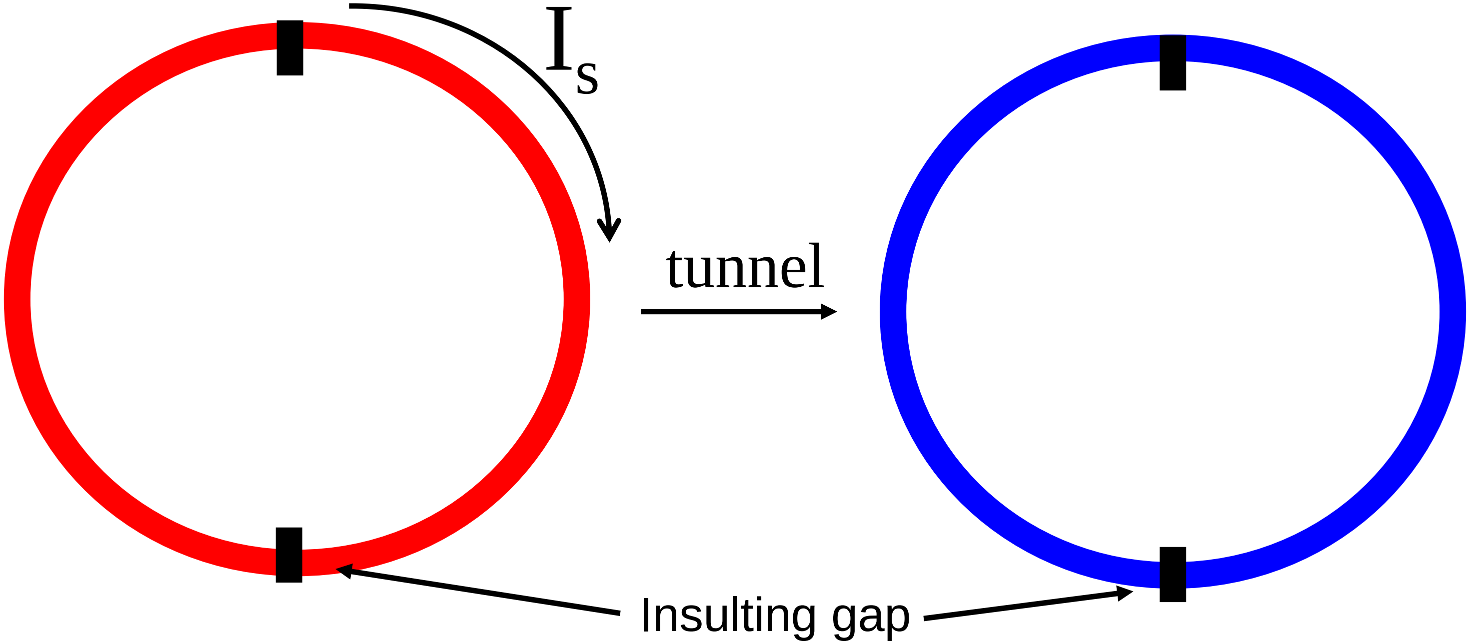
What sort of tunneling we will consider?



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

-Blue color represents no current or a much smaller current in the loop

Previous results relate loops with insulating interruptions (SQUIDs)



-Red color represents some strong current in the superconducting loop

-Blue color represents no current or very little current in the superconducting loop

Leggett's prediction for macroscopic quantum tunneling (MQT) in SQUIDs

80 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)

It is this property which makes a SQUID the most promising candidate to date for observing macroscopic quantum tunnelling; if it should ever become possible to observe macroscopic quantum *coherence*, the low entropy and consequent lack of dissipation will be absolutely essential.[21]

MQT report by Kurkijarvi and collaborators (1981)

VOLUME 47, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1981

Decay of the Zero-Voltage State in Small-Area, High–Current-Density Josephson Junctions

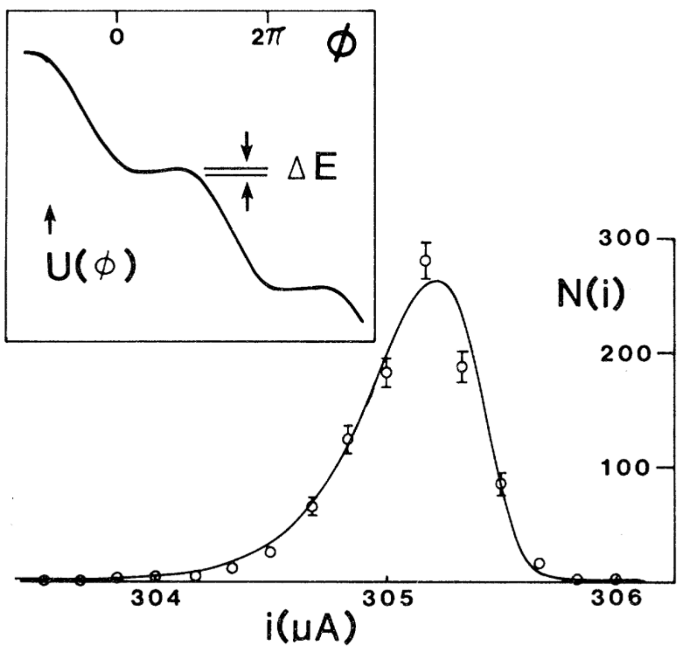


FIG. 1. Measured distribution for $T = 1.6$ K for small high–current-density junction. The solid line is a fit by the CL theory for $R = 20\ \Omega$, $C = 8$ fF, and $i_{cFF} = 310.5\ \mu$A. The inset is $U(\varphi)$ for $x = 0.8$ with barrier ΔE.

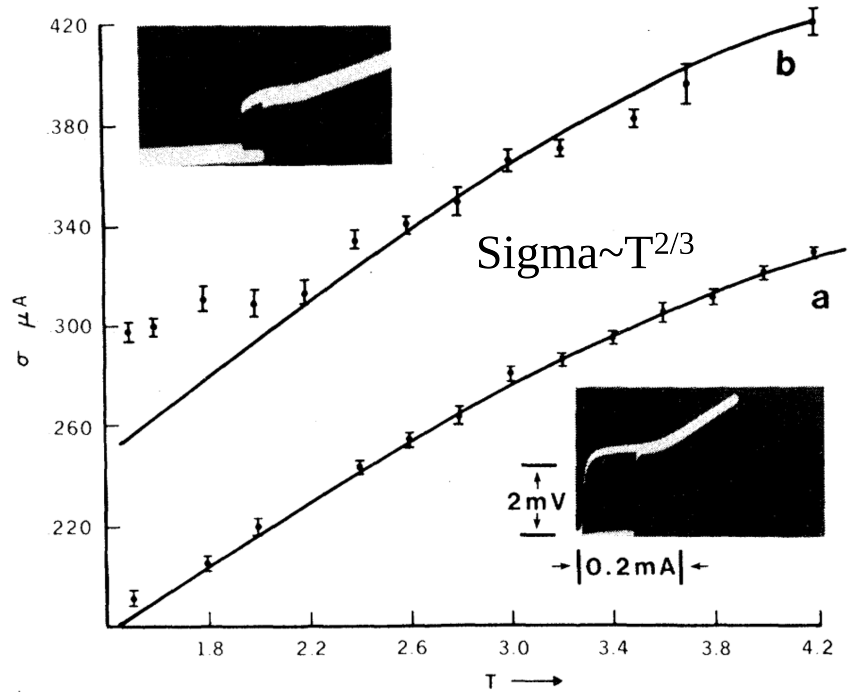
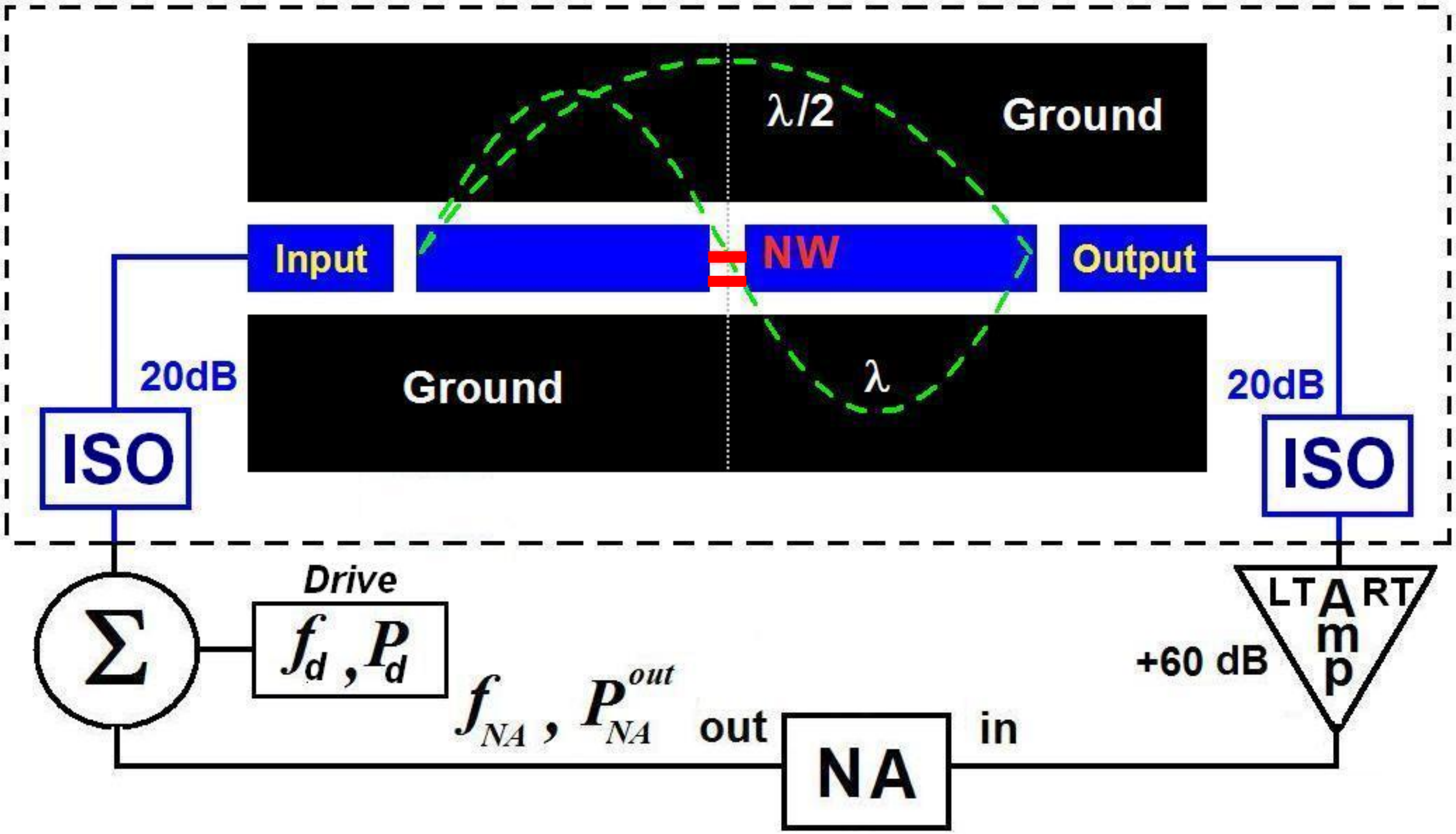


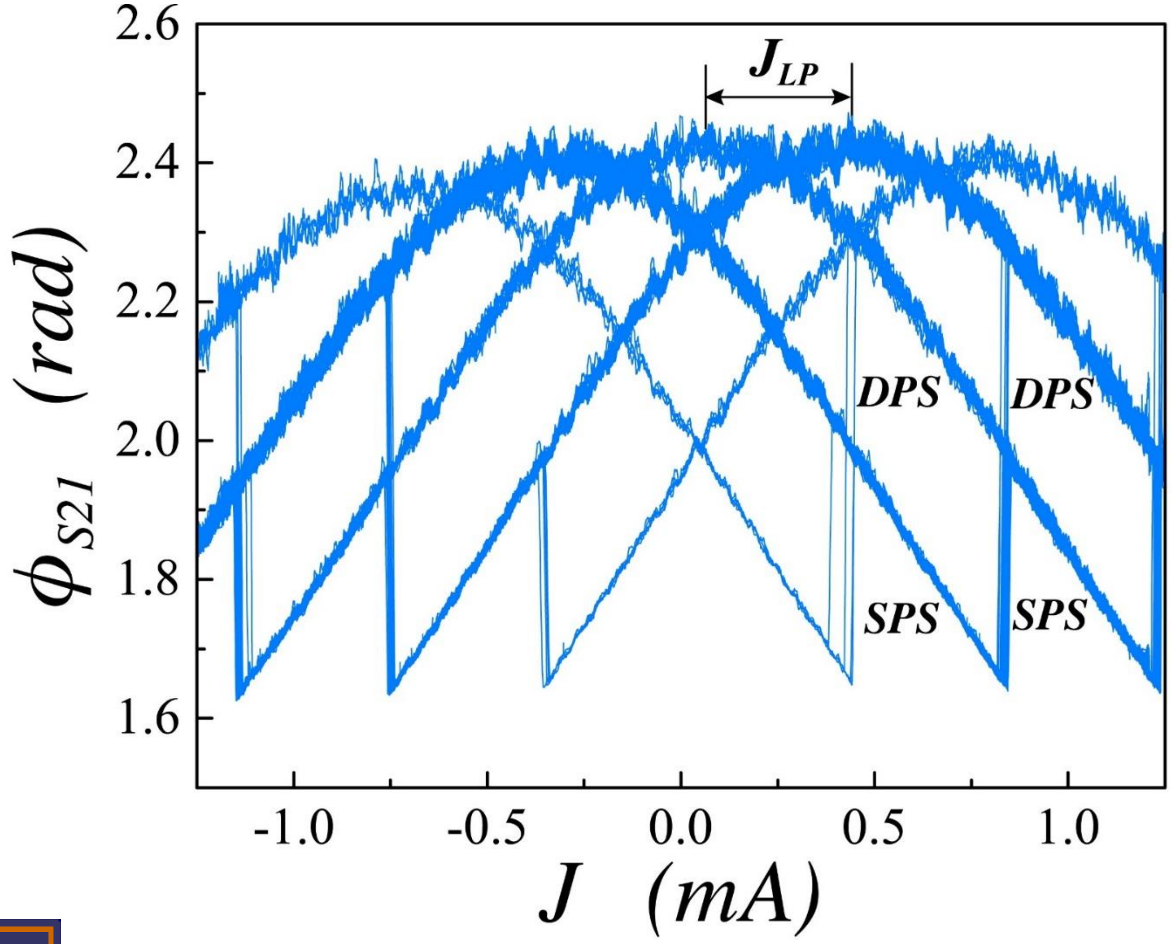
FIG. 2. Measured distribution widths σ vs T for two junctions with current sweep of ~400 μA/sec. Curve a is lower current density junction data and curve b is higher density junction data. The traces adjacent to the plots are the corresponding I–V characteristics at 4.2 K. The scales are the same for both traces.

Measuring nanowires within GHz resonators. Detection of individual phase slips.



A. Belkin et al, *Appl. Phys. Lett.* **98**, 242504 (2011)

Resonators used to detect single phase slips (SPS) and double phase slips (DPS)



T = 360 mK
$f = f_0(H=0)$

A. Belkin et al, PRX **5**, 021023 (2015)

Conclusions

- Superconductivity is fun and has proven to be useful for many applications

- The main goals now are:

    - (1) Discover superconducting materials which become superconducting at room temperature

    - (2) Use macroscopic quantum tunneling effects to develop superconducting quantum computers

    - (3) Develop superconducting memory for future cryogenic computers

TM