6.763 Applied Superconductivity
Lecture 1

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Dept. of Electrical Engineering
MIT

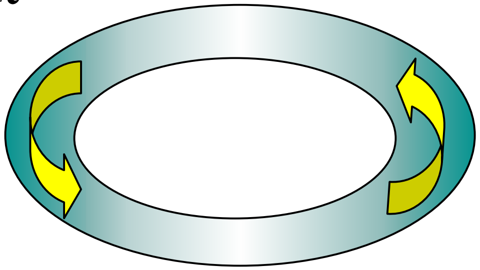
September 4, 2003

Outline

- What is a Superconductor?
- Discovery of Superconductivity
- Meissner Effect
- Type I Superconductors
- Type II Superconductors
- Theory of Superconductivity
- Tunneling and the Josephson Effect
- High-Temperature Supercondutors
- Applications of Superconductors

What is a Superconductor?

"A ***Superconductor*** has *ZERO* electrical resistance *BELOW* a certain critical temperature. Once set in motion, a persistent electric current will flow in the superconducting loop *FOREVER* without any power loss."



<u>Magnetic Flux explusion</u>

A ***Superconductor*** *EXCLUDES* any magnetic fields that come near it.

How “Cool” are Superconductors?

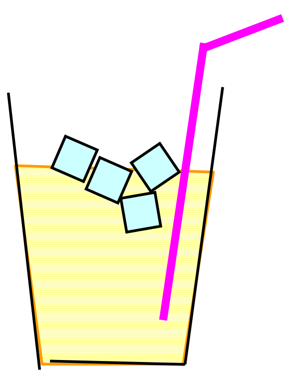
Below **77 Kelvin** (-200 ºC):

• Some Copper Oxide Ceramics superconduct

Below **4 Kelvin** (-270 ºC):

• Some Pure Metals e.g. Lead, Mercury, Niobium superconduct

<u>Keeping at 0 ºC</u>



<u>Keeping at 77 K</u>

<u>Keeping at 4K</u>

The Discovery of Superconductivity 1911

The Nobel Prize in Physics 1913

"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"

Heike Kamerlingh Onnes

the Netherlands

Leiden University
Leiden, the Netherlands

b. 1853
d. 1926

•http://www.nobel.se/physics/laureates

LOW TEMPERATURE STUDIES; LIQUID HELIUM 321

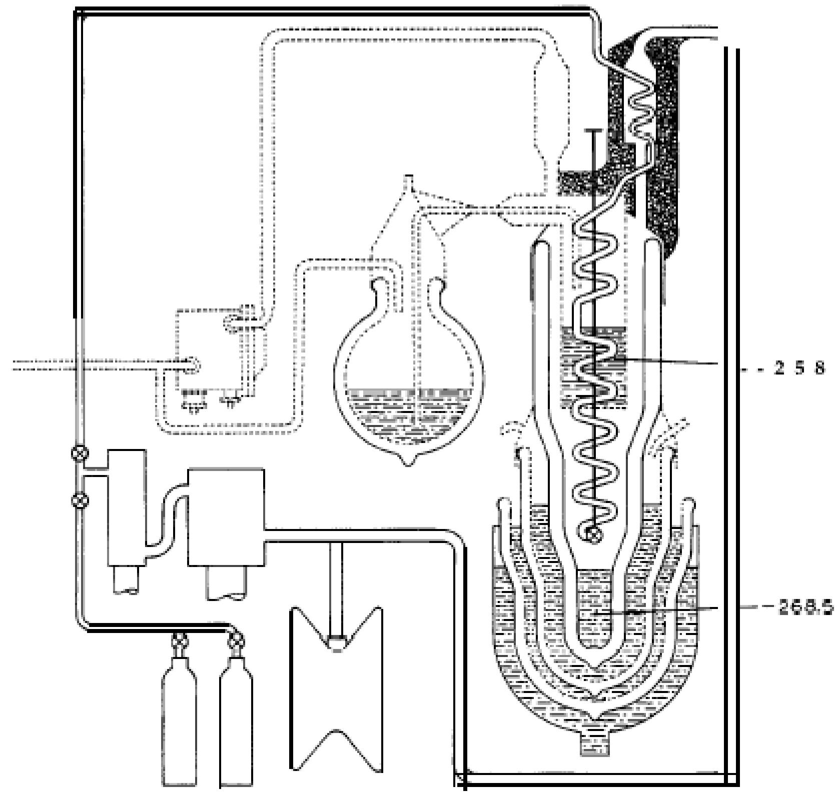


Fig. 7.

Discovery of Superconductivity

"As has been said, the experiment left no doubt that, as far as accuracy of measurement went, the resistance disappeared. At the same time, however, something unexpected occurred. The disappearance did not take place gradually but (compare Fig. 17) *abruptly*. From 1/500 the resistance at 4.2°K drop to a millionth part. At the lowest temperature, 1.5°K, it could be established that the resistance had become less than a thousand-millionth part of that at normal temperature.

Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity."

Heike Kamerlingh Onnes, Nobel Lecture

Resistance

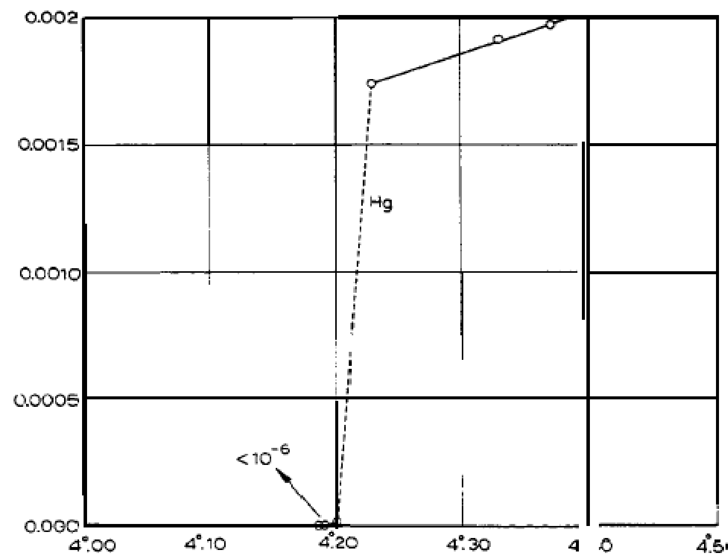
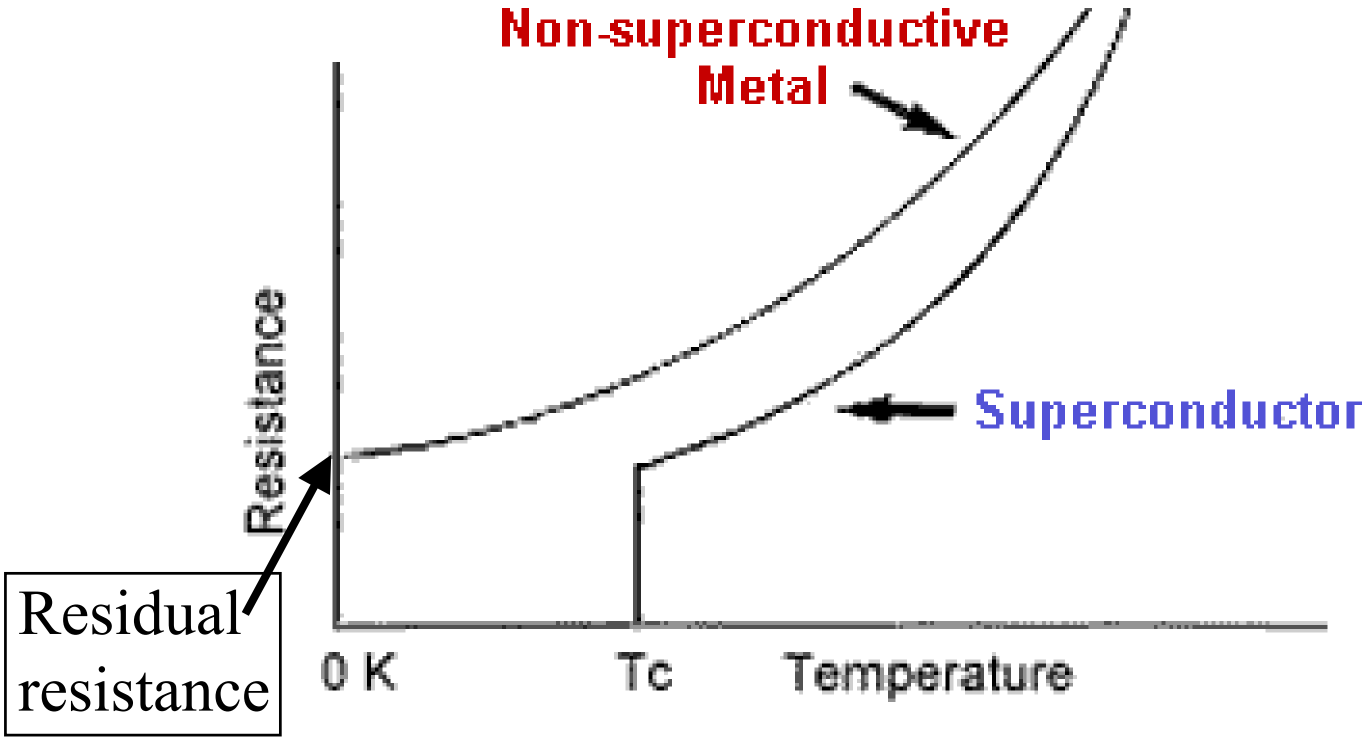


Fig. 17.

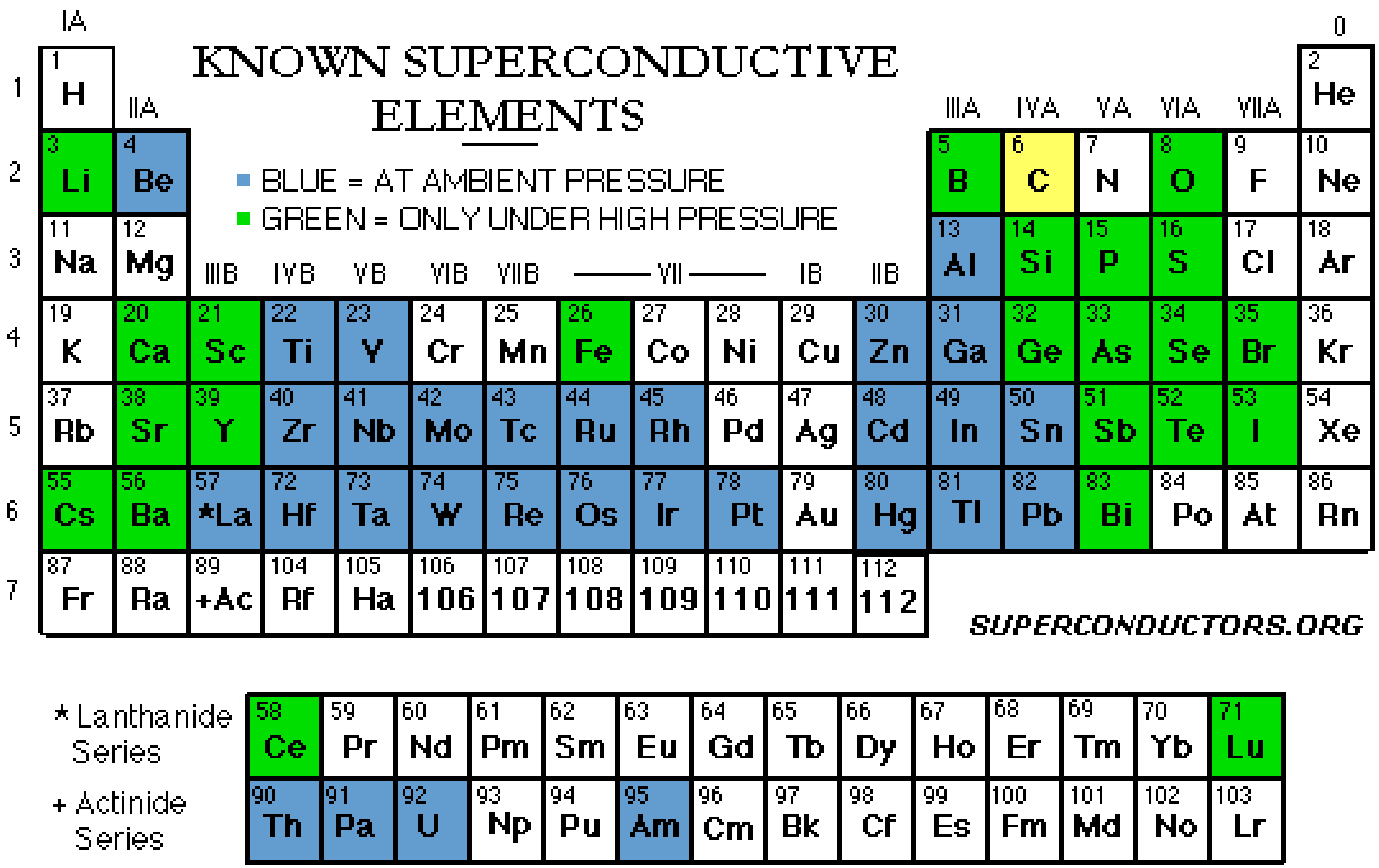
Temperature

•http://www.nobel.se/physics/laureates

Normal Metal vs Superconductor



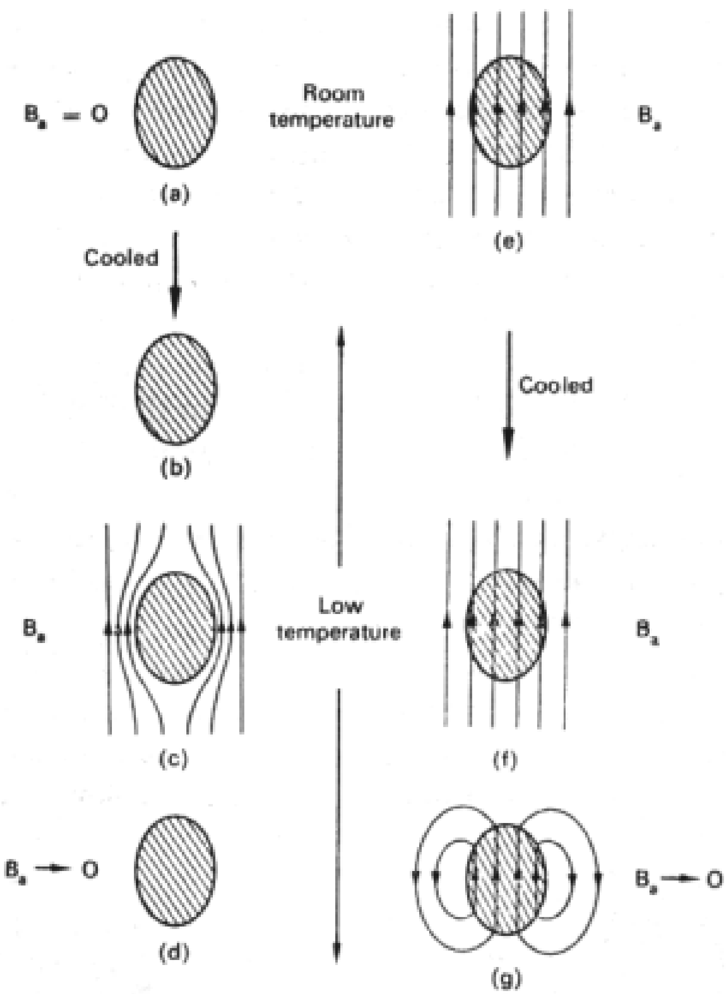
Periodic Table of Elements



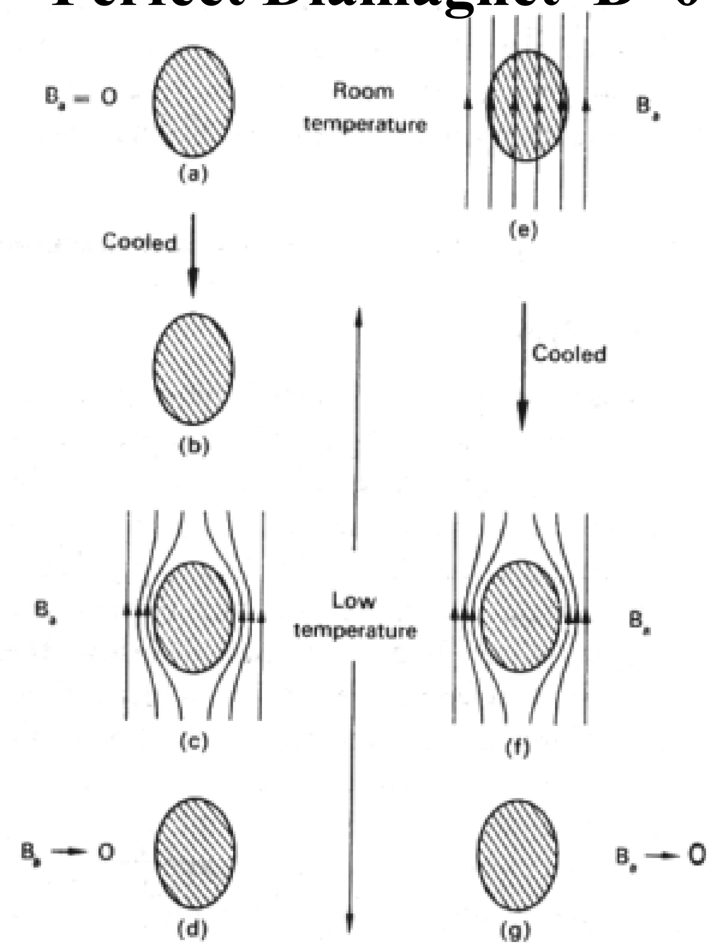
•http://www.superconductors.org/Type1.htm

A Superconductor is more than a perfect conductor, it is a Perfect Diamagnetism

Perfect Conductor R=0

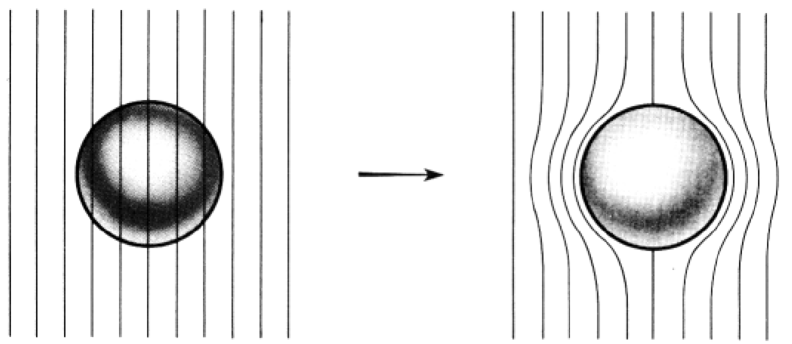


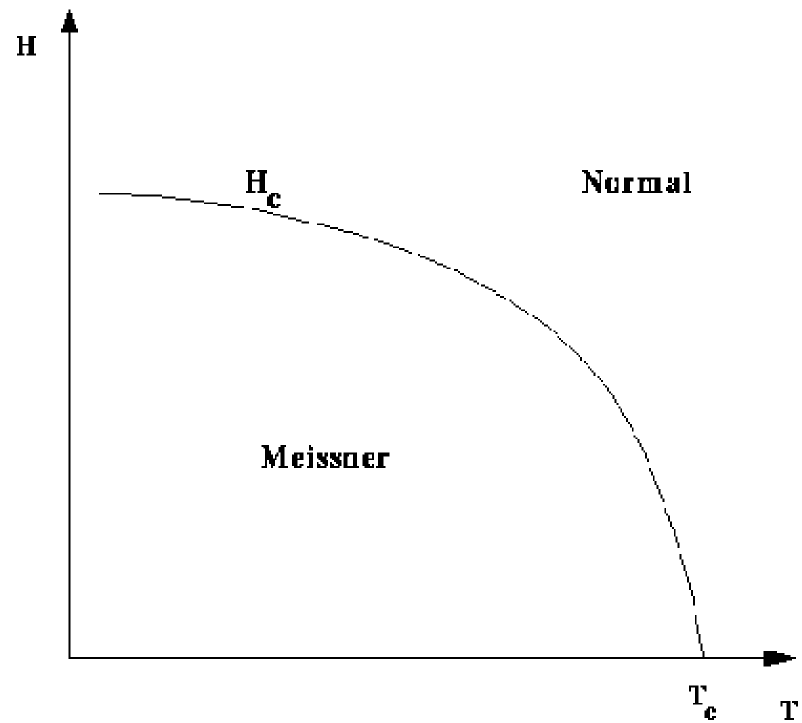
Perfect Diamagnet B=0



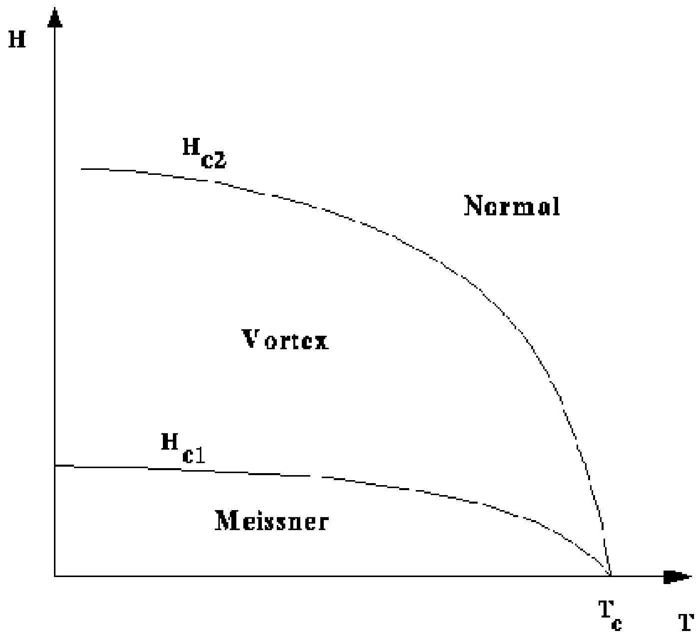
Meissener Effect

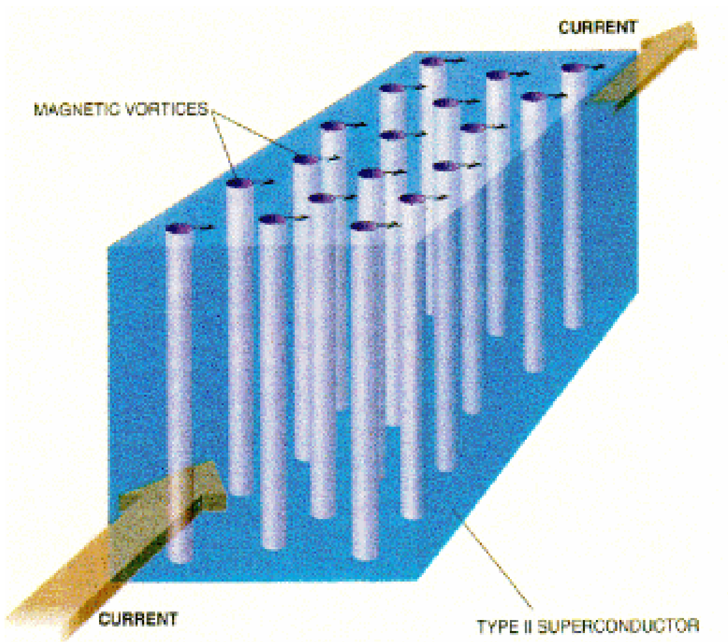
Type-I Superconductor





Type-II Superconductor



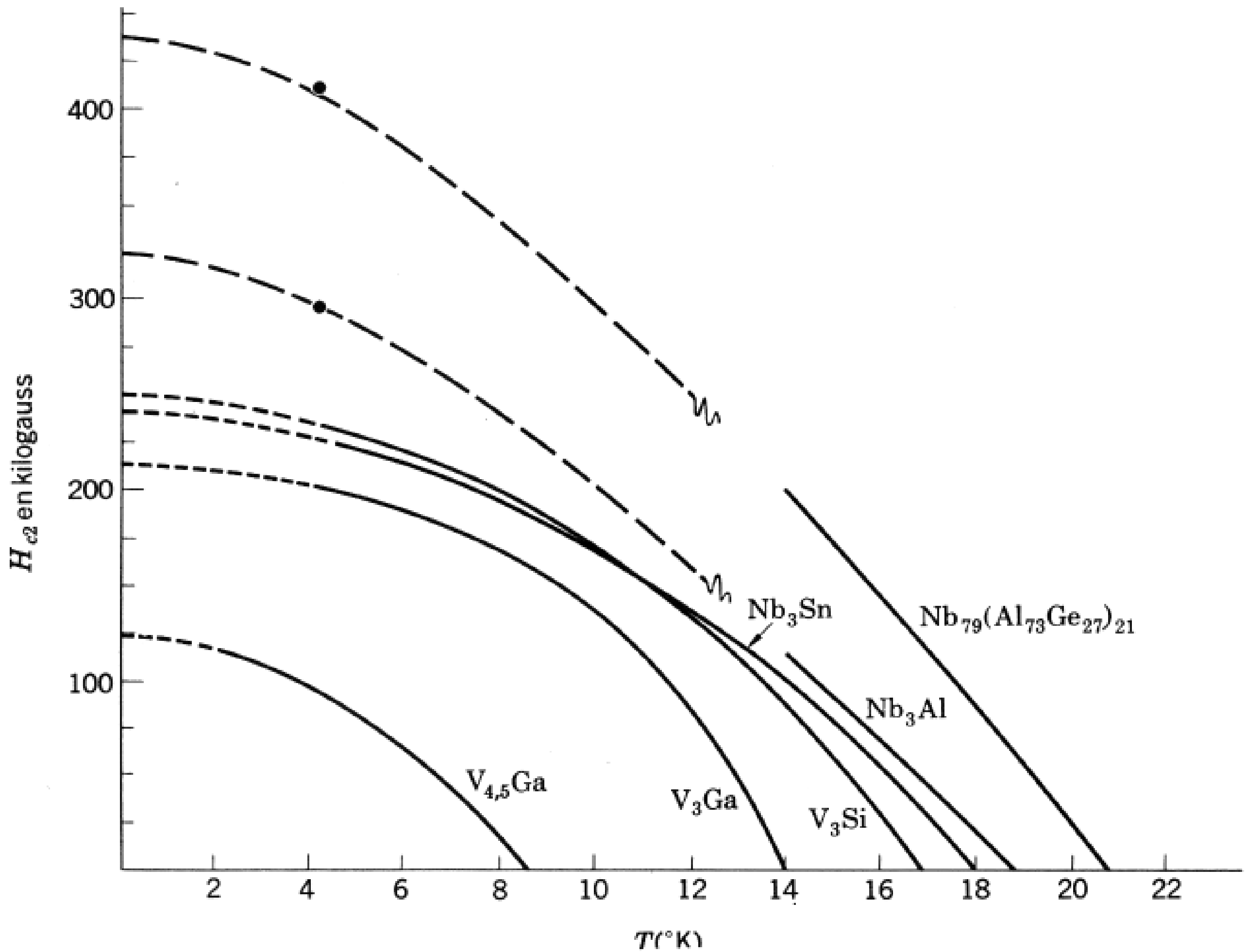


A current-carrying type II superconductor in the mixed state

When a current is applied to a type II superconductor (blue rectangular box) in the mixed state, the magnetic vortices (blue cylinders) feel a force (Lorentz force) that pushes the vortices at right angles to the current flow. This movement dissipates energy and produces resistance [from D. J. Bishop et al., Scientific American, 48 (Feb. 1993)].

http://phys.kent.edu/pages/cep.htm

Upper Critical Fields of Type II Superconductors



BCS Theory of Superconductivity

The Nobel Prize in Physics 1972

- "for their jointly developed theory of superconductivity, usually called the BCS-theory"

John Bardeen	Leon Neil Cooper	John Robert Schrieffer
1/3 of the prize	1/3 of the prize	1/3 of the prize
USA	USA	USA
University of Illinois Urbana, IL, USA	Brown University Providence, RI, USA	University of Pennsylvania Philadelphia, PA, USA
b. 1908 d. 1991	b. 1930	b. 1931

- http://www.nobel.se/physics/laureates

ELECTRON-PHONON INTERACTIONS AND SUPERCONDUCTIVITY

Nobel Lecture, December 11, 1972

By JOHN BARDEEN

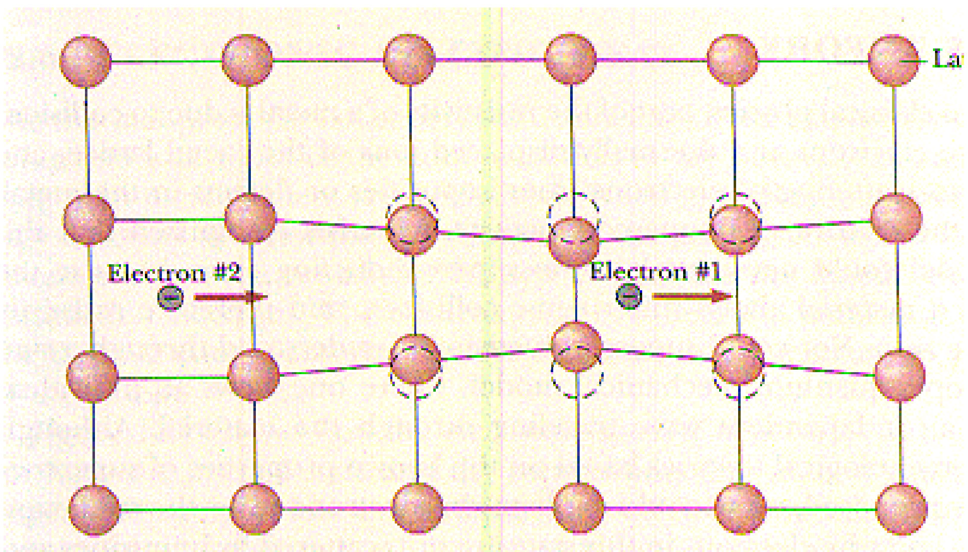
Departments of Physics and of Electrical Engineering

University of Illinois Urbana, Illinois

INTRODUCTION

Our present understanding of superconductivity has arisen from a close interplay of theory and experiment. It would have been very difficult to have arrived at the theory by purely deductive reasoning from the basic equations of quantum mechanics. Even if someone had done so, no one would have believed that such remarkable properties would really occur in nature. But, as you well know, that is not the way it happened, a great deal had been learned about the experimental properties of superconductors and phenomenological equations had been given to describe many aspects before the microscopic theory was developed.

The Electron-phonon Interaction



The origin of superconductivity in conventional superconductors

http://www.physics.carleton.ca/courses/75.364/mp-2html/node16.html

Cooper Pairs & Energy Gap

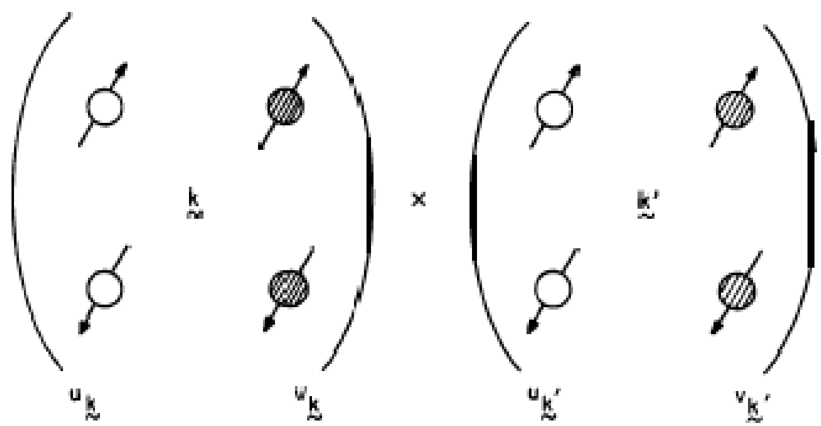


Fig. 5.
A decomposition of the ground state of the superconductor into states in which the pair states k and k' are either occupied or unoccupied.

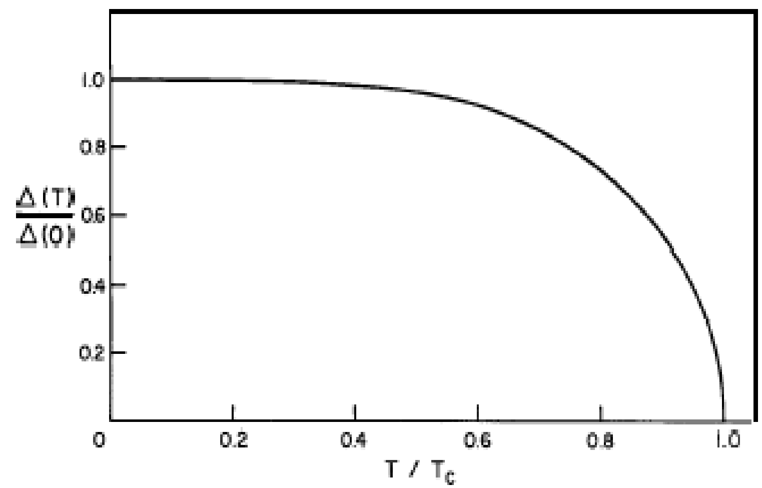
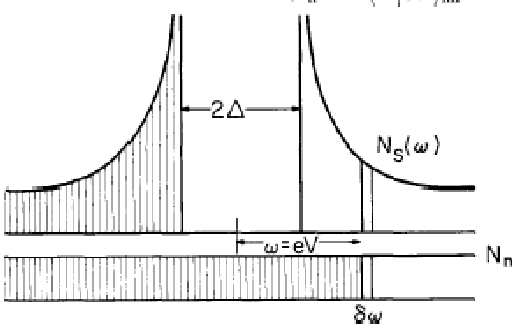


Fig. 7.
Variation of the energy gap with temperature for the ideal superconductor.

http://www.nobel.se/physics/laureates/1972/cooper-lecture.pdf

Superconducting Energy Gap

$$\frac{\mathcal{N}_s(eV)}{\mathcal{N}_n} = \frac{(dI/dV)_{ns}}{(dI/dV)_{nn}} \qquad (18)$$



$$\left(\frac{dI}{dV}\right)_{ns} \sim N_S(\omega) \sim \frac{\omega}{\sqrt{\omega^2-\Delta^2}}$$

Tunneling from a normal metal into a superconductor

Fig. 1.

Schematic diagram illustrating tunneling from a normal metal into a superconductor near $T = 0°K$. Shown in the lower part of the diagram is the uniform density of states in energy of electrons in the normal metal, with the occupied states shifted by an energy eV from an applied voltage V across the junction. The upper part of the diagram shows the density of states in energy in the superconductor, with an energy gap 2Δ. The effect of an increment of voltage δV giving an energy change $\delta\omega$ is to allow tunneling from states in the range $\delta\omega$. Since the tunneling probability is proportional to density of states $N_s(\omega)$, the increment in current δI is proportional to $N_s(\omega)\delta V$.

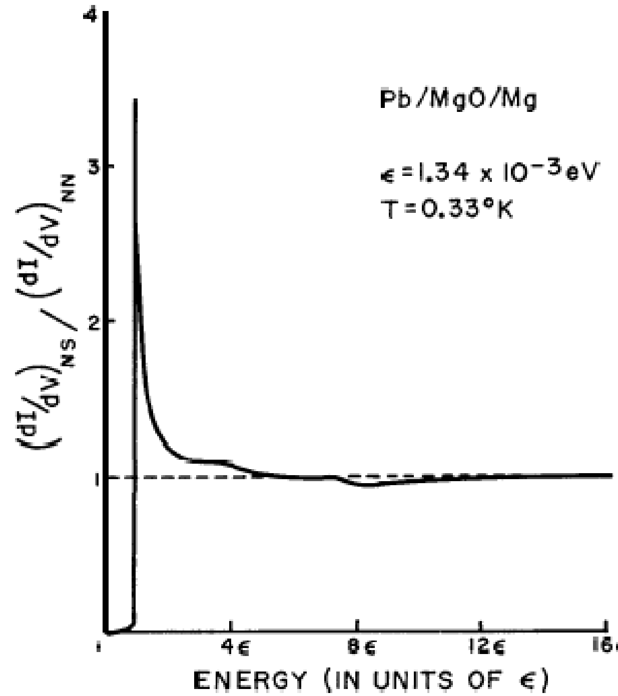


Fig. 2.

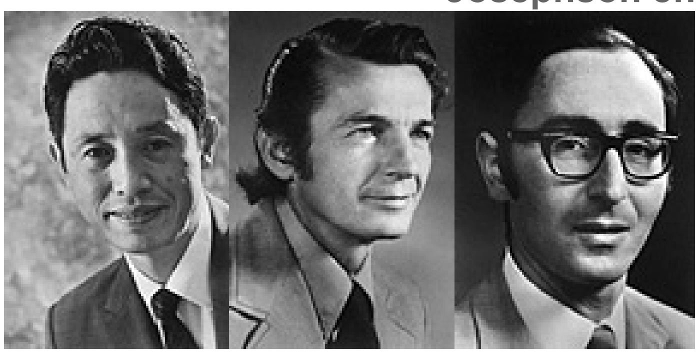
Conductance of a Pb-Mg junction as a function of applied voltage (from reference 24).

http://www.nobel.se/physics/laureates/1972/bardeen-lecture.pdf

The Nobel Prize in Physics 1973

"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"

"for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"



Leo Esaki	Ivar Giaever	Brian David Josephson
1/4 of the prize	1/4 of the prize	1/2 of the prize
Japan	USA	United Kingdom
IBM Thomas J. Watson Research Center Yorktown Heights, NY, USA	General Electric Company Schenectady, NY, USA	University of Cambridge Cambridge, United Kingdom
b. 1925	b. 1929 (in Bergen, Norway)	b. 1940

138 Physics 1973

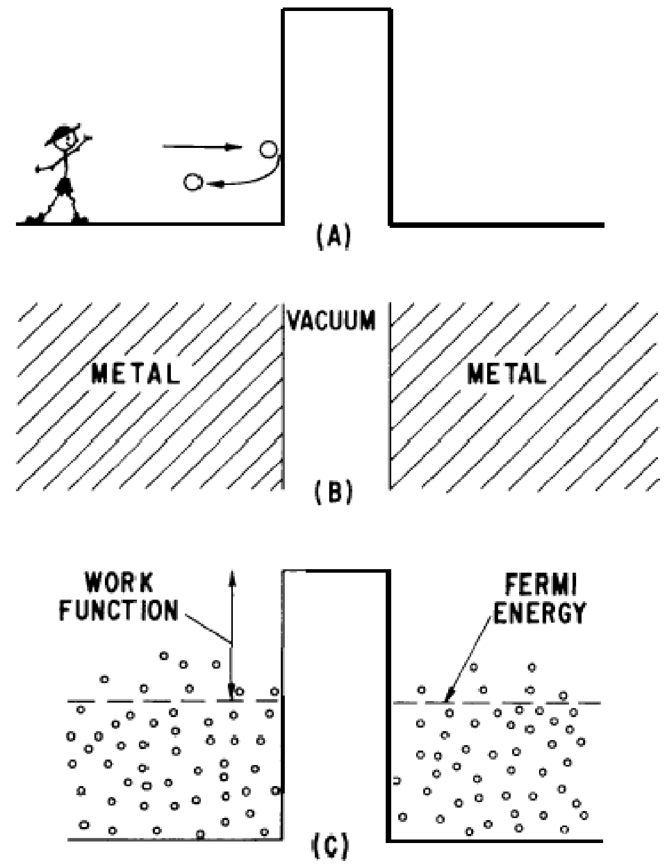


Fig. 1.

•http://www.nobel.se/physics/laureates

Tunneling between a normal metal and another normal metal or a superconductor

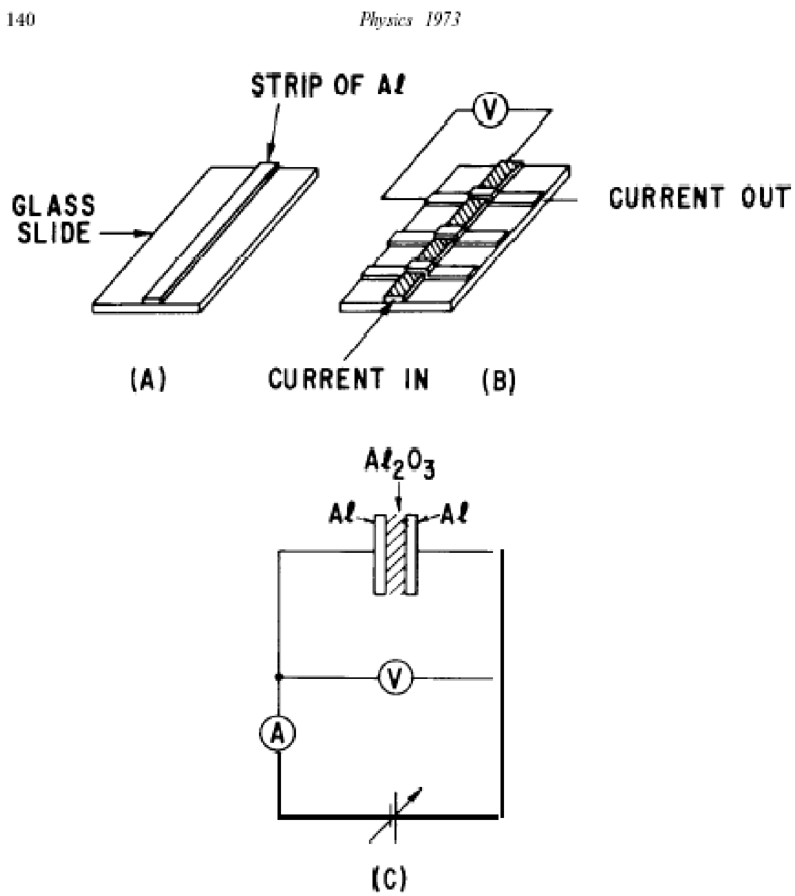


Fig. 3.

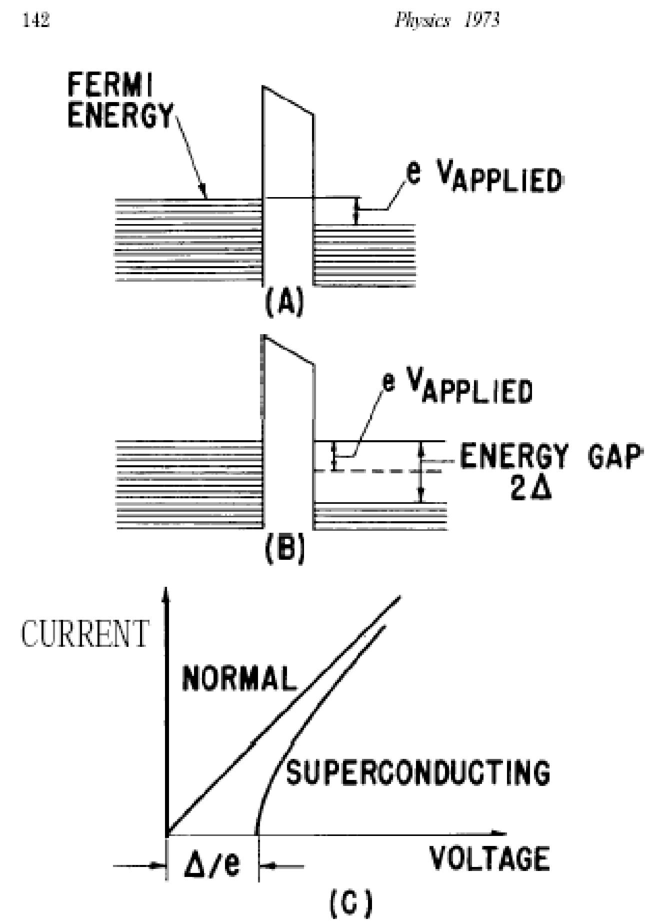


Fig. 5.

http://www.nobel.se/physics/laureates/1973/giaever-lecture.pdf

Tunneling between two superconductors

148 *Physics 1973*

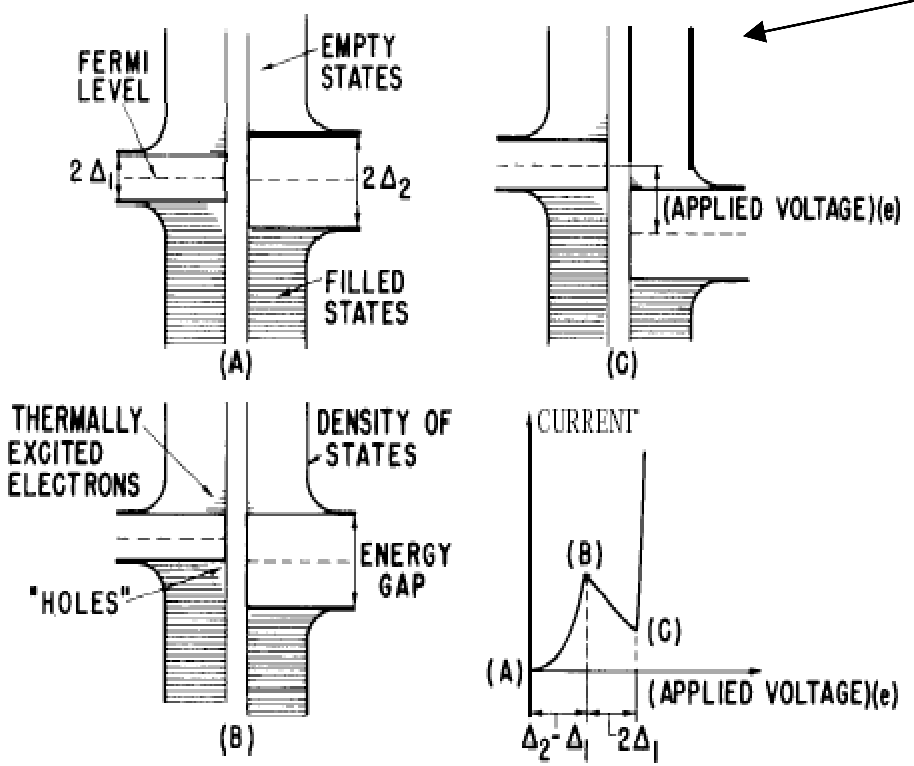
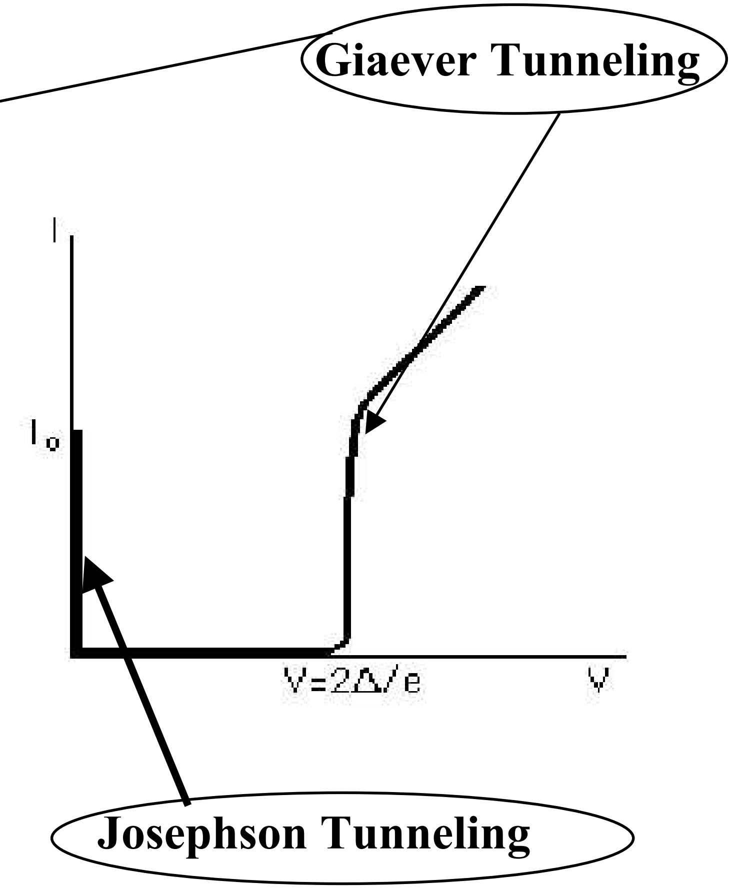
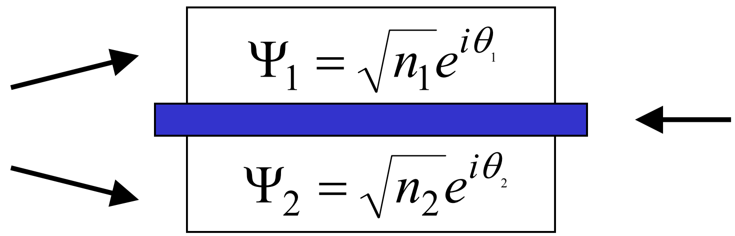


Fig. 10.
Tunneling between two superconductors with different energy gaps at a temperature larger than 0° K. A. No voltage is applied between the two conductors. B. As a voltage



Josephson Junction



- Josephson relations:

$$I = I_c \sin\varphi$$

$$V = \frac{\Phi_0}{2\pi}\frac{d\varphi}{dt}$$

$$\varphi = \theta_2 - \theta_1 - \frac{2\pi}{\Phi_0}\int_2^1 \vec{A}(r,t)\cdot d\vec{l}$$

- Behaves as a nonlinear inductor:

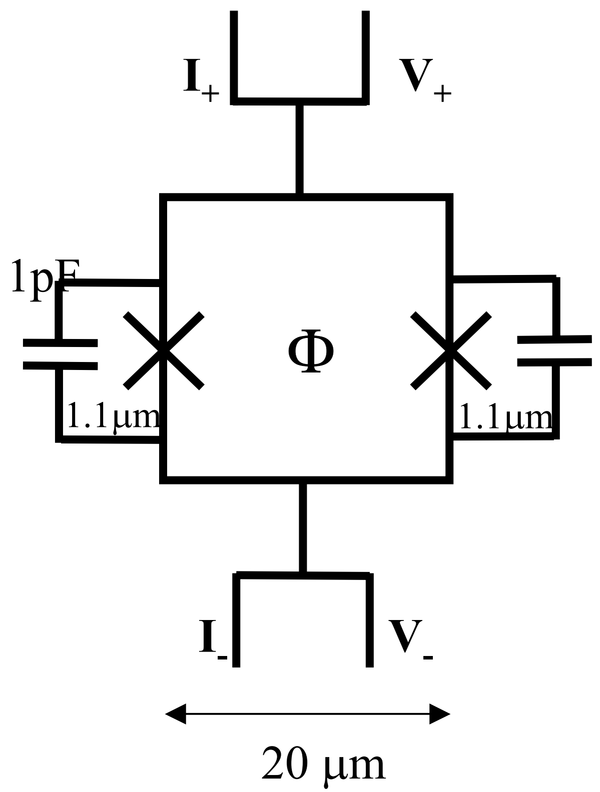
$$V = L_J \frac{dI}{dt},$$

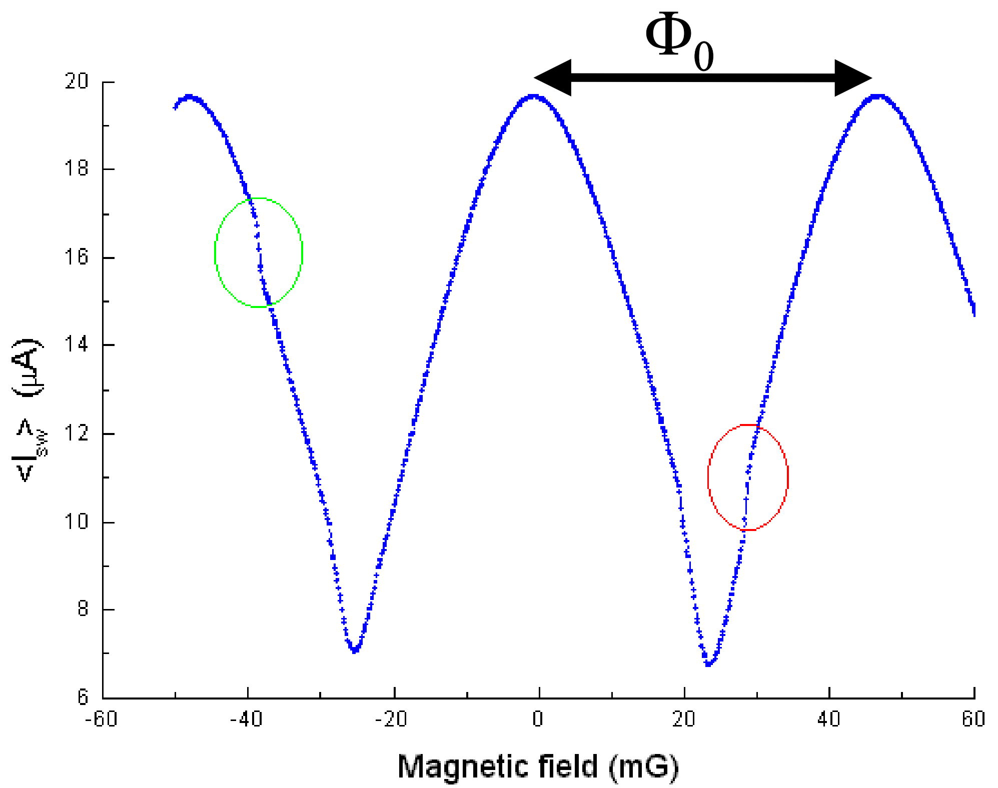
where $$L_J = \frac{\Phi_0}{2\pi\, I_c \cos\varphi}$$

Φ_0 = flux quantum

483.6 GHz / mV

SQUID Magnetometers





DC SQUID

Shunt capacitors ~ 1pF

Jct. Size ~ 1.1μm

Loop size ~20x20μm²

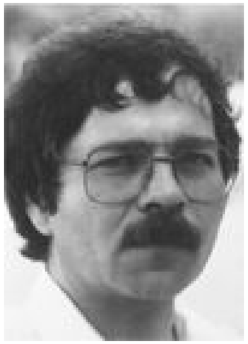
L_{SQUID} ~ 50pH

I_c~10 & 20μA

High-Temperature Superconductivity

The Nobel Prize in Physics 1987

"for their important break-through in the discovery of superconductivity in ceramic materials"



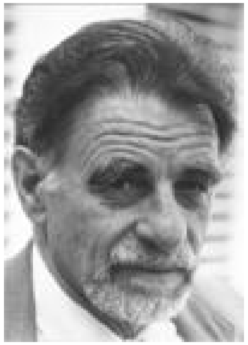
J. Georg Bednorz

1/2 of the prize

Federal Republic of Germany

IBM Zurich Research Laboratory
Rüschlikon, Switzerland

b. 1950



K. Alexander Müller

1/2 of the prize

Switzerland

IBM Zurich Research Laboratory
Rüschlikon, Switzerland

b. 1927

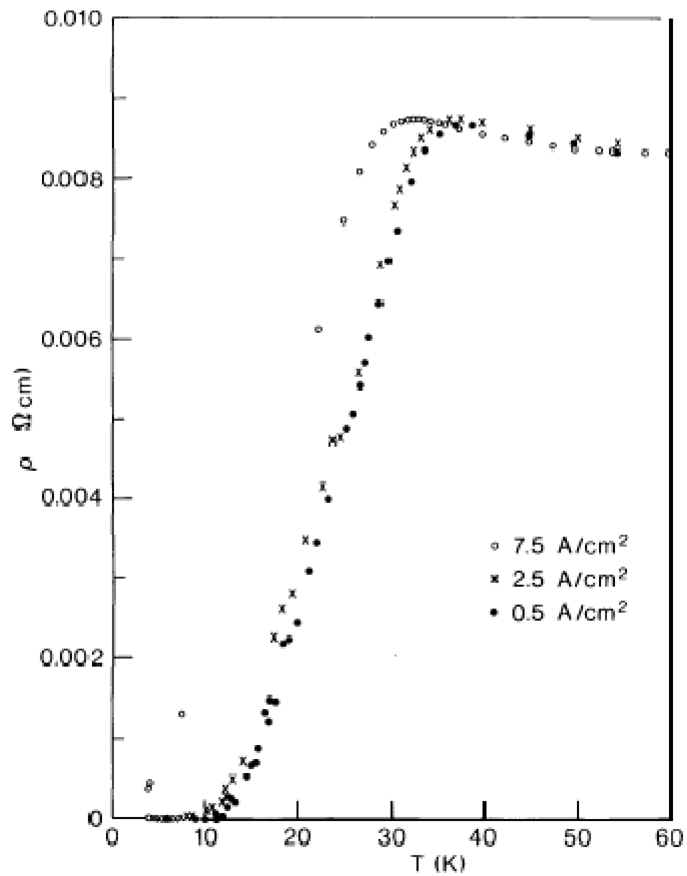


Figure 1.5. Low-temperature resistivity of a sample with x(Ba) = 0.75, recorded for different current densities. From [1.19], © Springer-Verlag 1986.

•http://www.nobel.se/physics/laureates

High-Temperature Superconductors

J. G. Bednorz & K. A. Müller 441

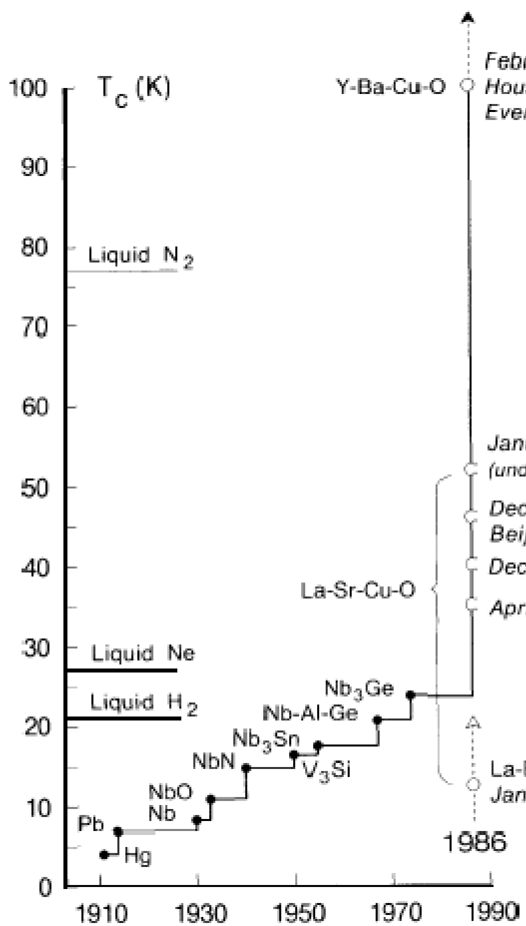


Figure 1.13. Evolution of the superconductive transition temperature subsequent to the discovery of the phenomenon. From [1.29]. © 1987 by the American Association for the Advancement of Science.

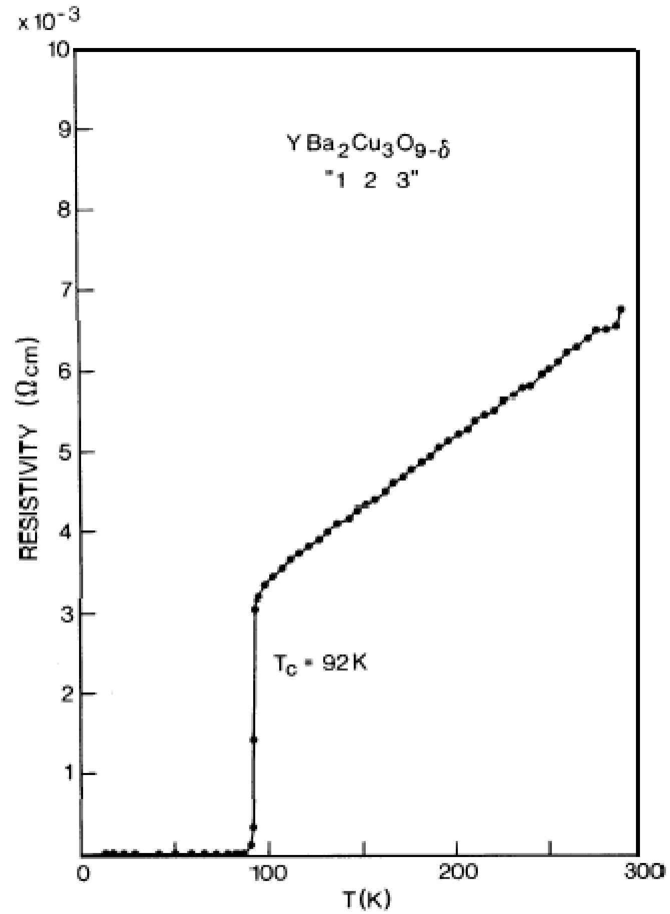
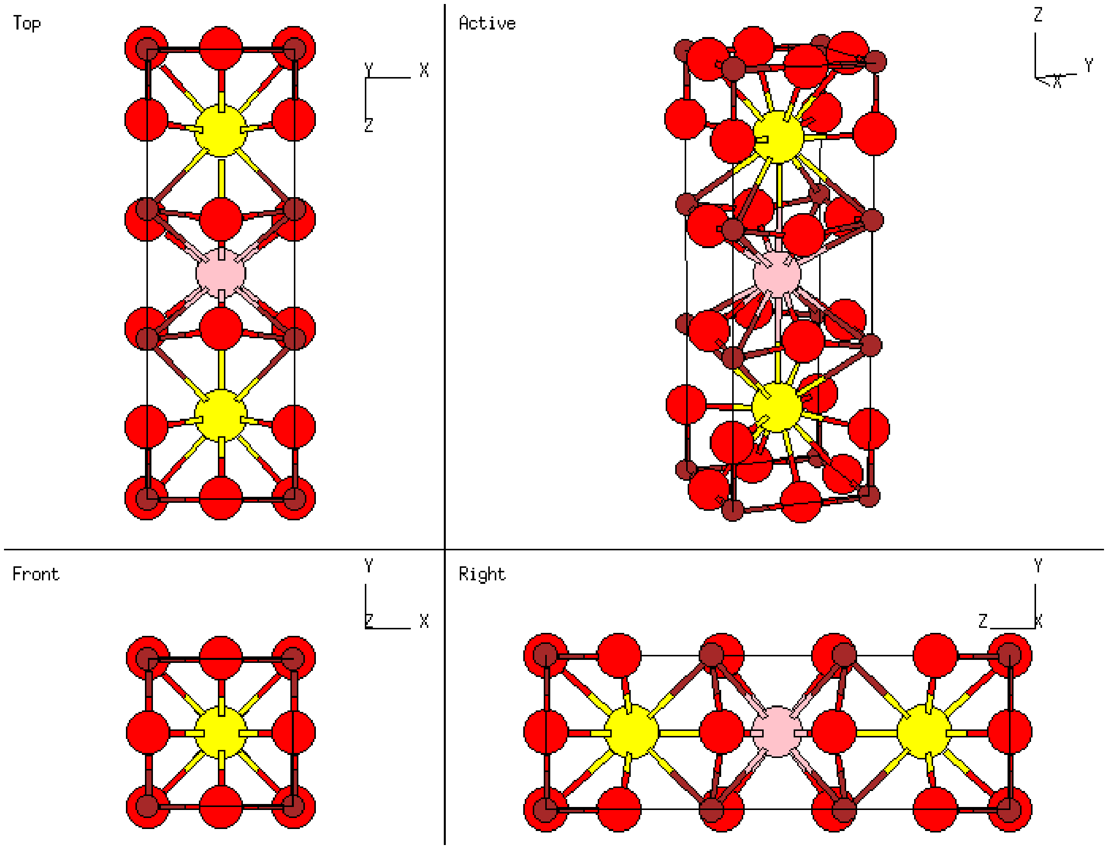


Figure 1.14. Resistivity of a single-phase $YBa_2Cu_3O_7$ sample as a function of temperature.

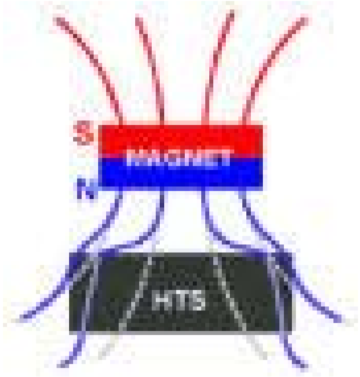
http://www.nobel.se/physics/laureates/1987/bednorz-muller-lecture.pdf

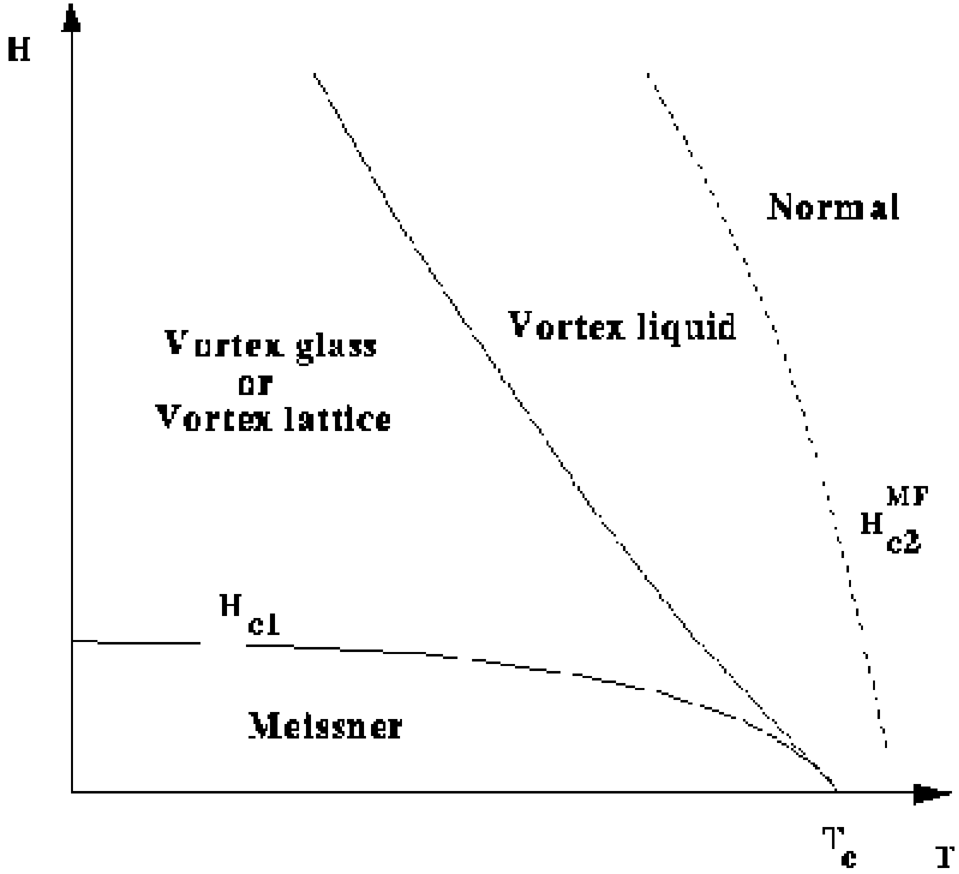
Perovskite Structure



•http://cst-www.nrl.navy.mil/lattice/struk/perovskite.html

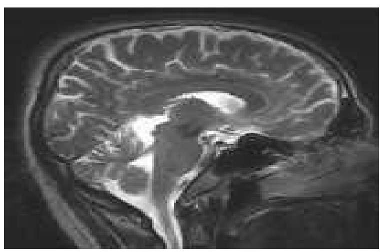
High-Temperature Superconductor





Uses for Superconductors

- Magnetic Levitation allows trains to “float” on strong superconducting magnets (MAGLEV in Japan, 1997)



- To generate Huge Magnetic field e.g. for Magnetic Resonance Imaging (MRI)

- A SQUID (Superconducting Quantum Interference Device) is the most sensitive magnetometer. (sensitive to 100 billion times weaker than the Earth’s magnetic field)

- Quantum Computing

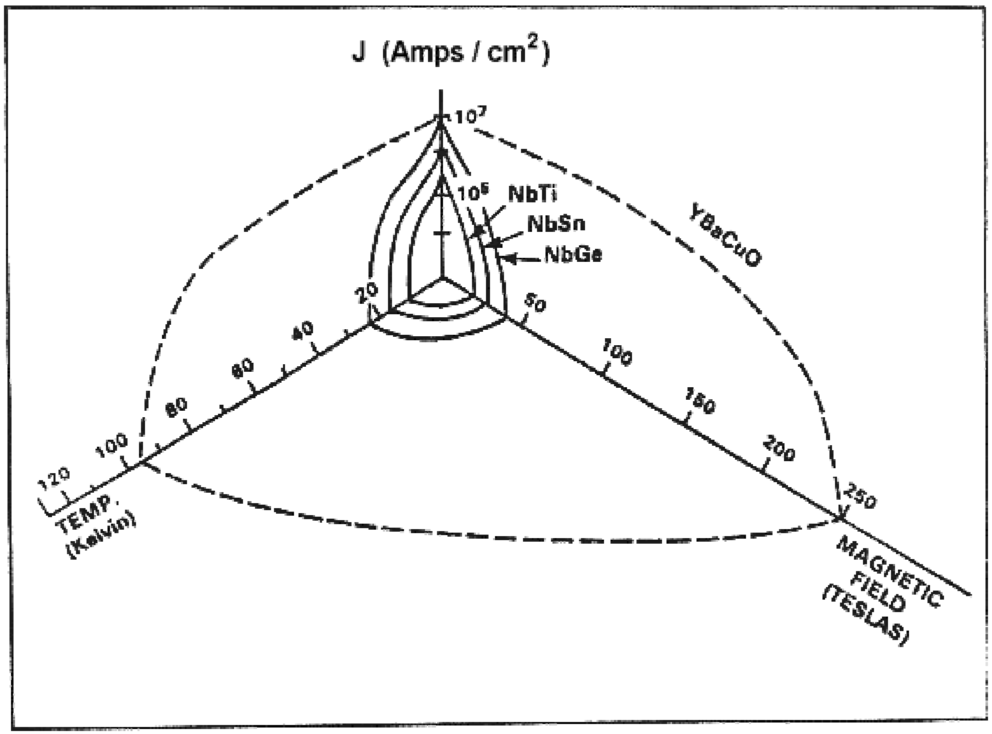
Picture source: http://www.superconductors.org

Large-Scale Applications

Application	Techinical Points
Power cables	High current densities
Current Limiters	Uses highly nonlinear nature of transition
Transformers	High current densities and magentic fields, has lower losses
Motors/Generators	Smaller weight and size, lower losses
Energy Storage Magnets	Need high fields and currents Smaller weight and size, lower losses
NMR magnets (MRI)	Ultra high field stability, large air gaps
Cavities for Accelerators	High microwave powers
Magnetic bearins	Low losses, self-controlled levitation

Adapted from http://www.conectus.org/xxroadmap.html

Phase Diagram of a Type II Superconductor



Phase Diagram

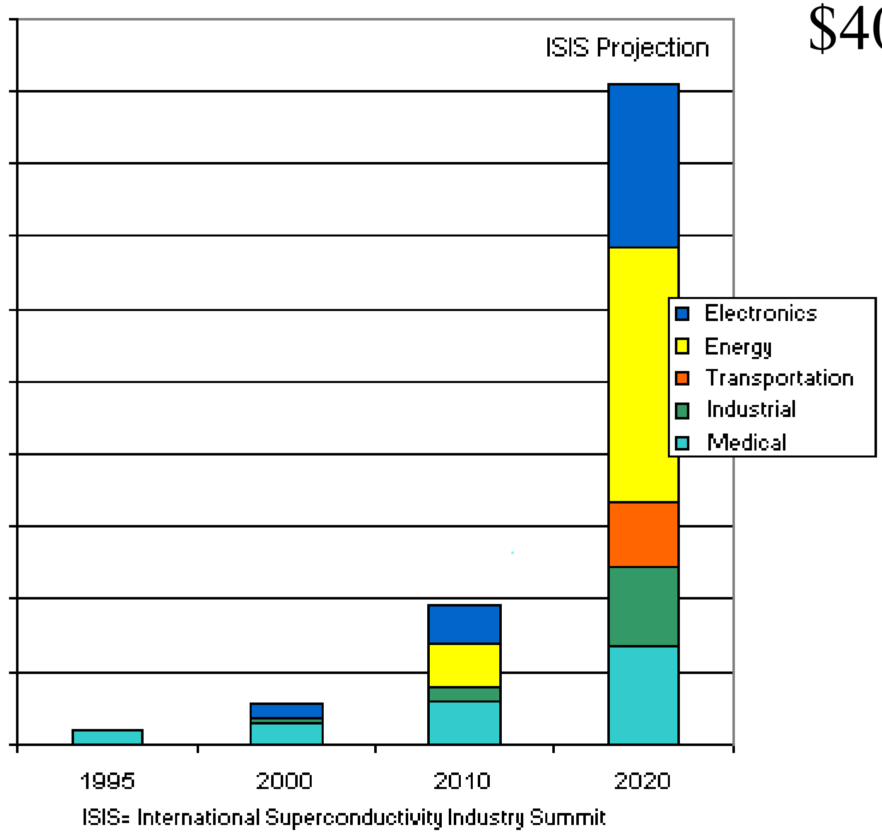
•http://www.futurescience.com/manual/sc1000.html#C

Small-Scale Applications

Application	Techinical Points
Microwave filters in cellular stations	Low losses, smaller size, sharp filtering
Passive microwave devices, Resonators for oscillators	Lower surface losses, high quality factors, small size
Far-infrared bolometers	nonlinear tunneling SIS curves, high sensitivity
Microwave detectors	Uses nonlinear tunneling SIS curves, high conversion efficiency for mixing
X-ray detectors	High photon energy resolution
SQUID Magnetometers: Magneto-encephalography, NDT	Ultra-high sensitivity to magnetic fields
Voltage Standards	Quantum precision
Digital Circuits (SFQ)	Up to 750 GHz, ultra-fast, low-power.

Adapted from http://www.conectus.org/xxroadmap.html

Economic Outlook



$40 billion

•http://www.superconductors.org/conectus.pdf

The Promise of a Quantum Computer

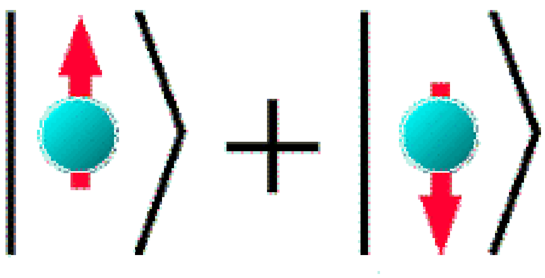
A Quantum Computer …

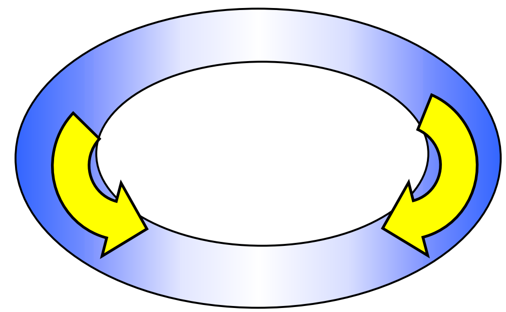
- Offers exponential improvement in ***speed*** and ***memory*** over existing computers
- Capable of ***reversible computation***
- e.g. Can factorize a 250-digit number in seconds while an ordinary computer will take 800 000 years!

⇨ Current Research in my group focuses on Quantum Computation using Superconductors

The "Magic" of Quantum Mechanics

States 0 and 1 are stored and processed AT THE SAME TIME

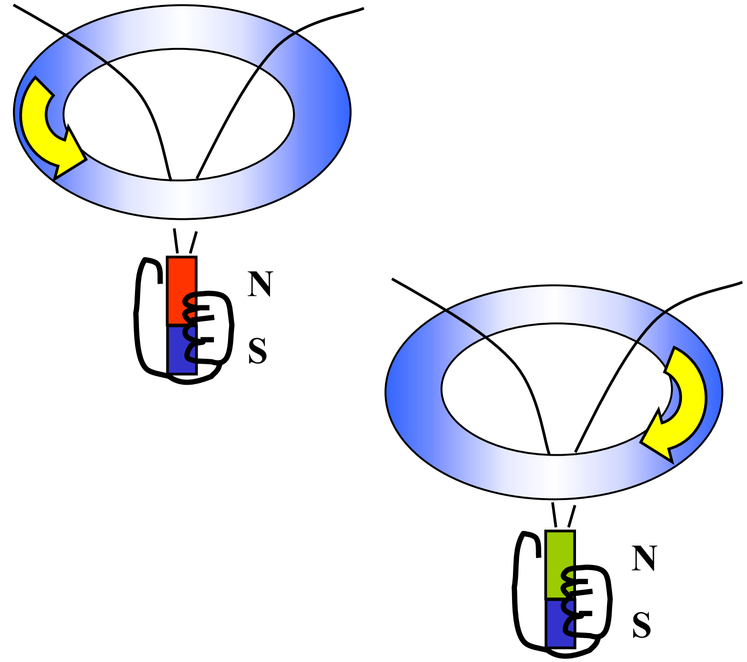




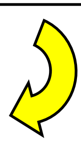
→ Parallel Computation → Exponential Speedup to get Answers

The Superconducting "Quantum Bit"

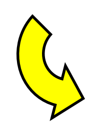
- An External Magnet can induce a current in a superconducting loop
- The induced current can be in the opposite direction if we carefully choose a *different* magnetic field this time



- To store and process information as a computer bit, we assign:

 as state $|\,0\,\rangle$

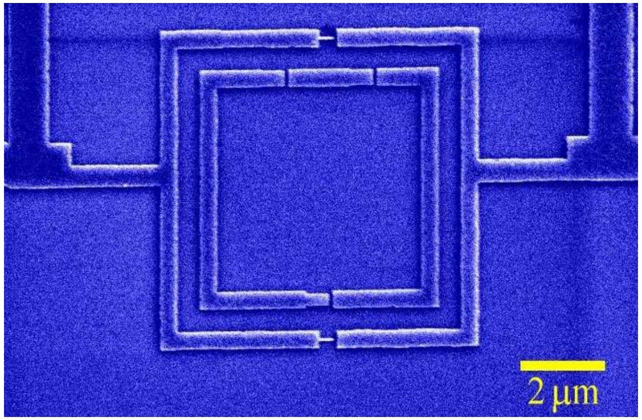
clockwise

 as state $|\,1\,\rangle$

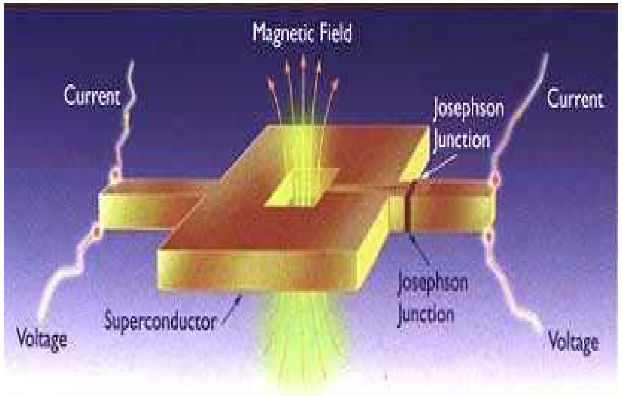
Anti-clockwise

Persistent Current Qubit

• Depending on the direction of the current, state $|0\rangle$ ↻ and state $|1\rangle$ ↺ will *add* a different magnetic field to the external magnet



• This difference is very small but can be distinguished by the extremely sensitive SQUID sensor



Our Approach to Superconductivity

Classical

Superconductor as a perfect conductor & perfect diamagnet

Macroscopic Quantum Model $\Psi(r)$

Supercurrent Equation $J_s(r)$

Type II Superconductivity

Large-Scale Applications

Josephson Equations

Small-Scale Applications

Ginzburg-Landau

$\Psi(r) = |\Psi(r)|^2 e^{i\theta(r,t)}$

BCS

Macroscopic Quantum Model

Microscopic Quantum