Superconductivity

Lecture is based on the talk “101 years of superconductivity”

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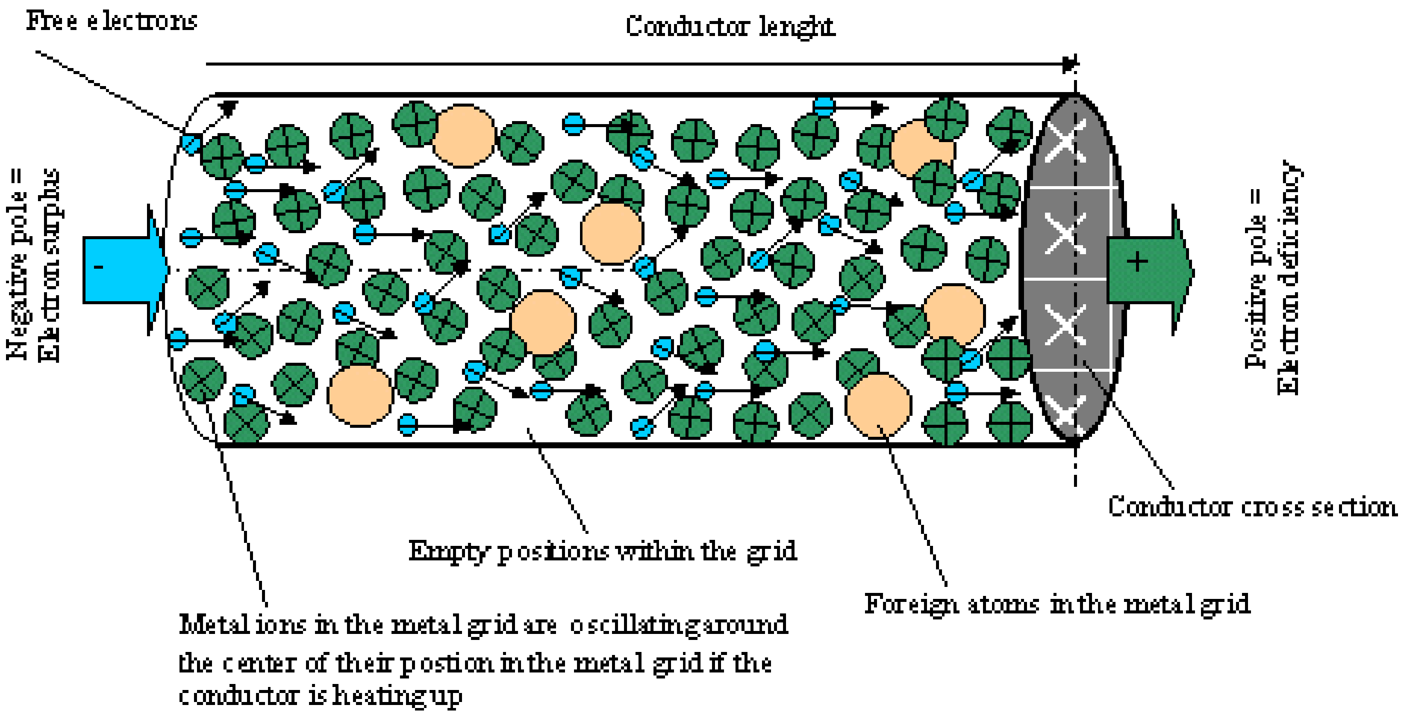
Laboratory for Developments and Methods,
Paul Scherrer Institute, Switzerland
Available online at:
http://collaborations.fz-juelich.de/ikp/cgswhp/cgswhp12/
program/files_batumi/14-08-2012/3_Cazimierz_Conder_101YearsSuperconductivityFinal.ppt

Conductors



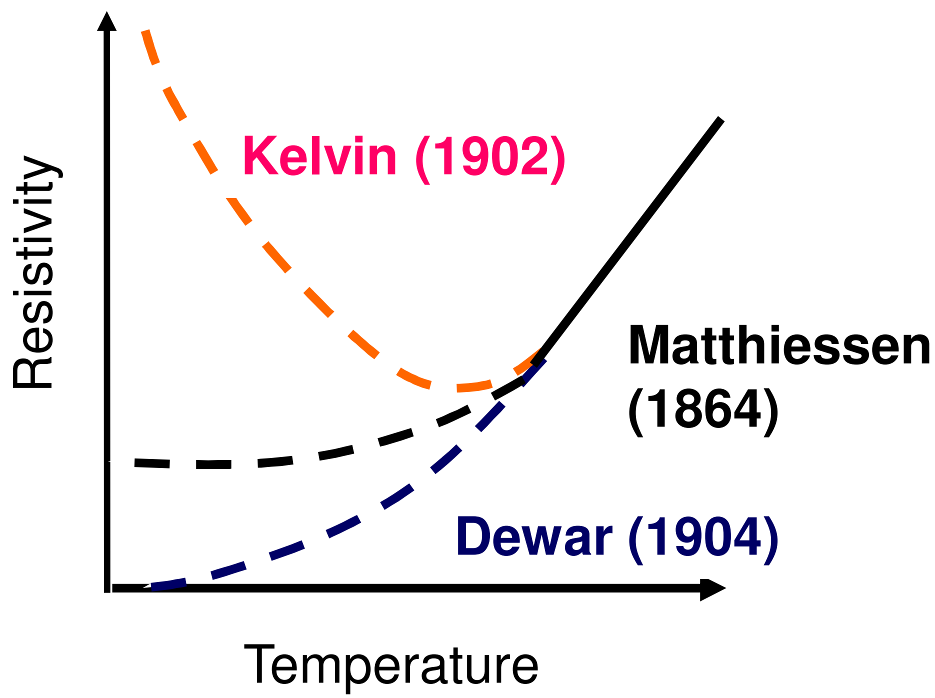
In a normal conductor, an electrical current may be visualized as a fluid of electrons moving across a heavy ionic lattice.

The electrons are constantly colliding with the ions in the lattice.

During each collision some of the energy carried by the current is absorbed by the lattice and converted into heat (which is essentially the vibrational kinetic energy of the lattice ions.) As a result, the energy carried by the current is constantly being dissipated. This is the phenomenon of electrical resistance.

Animation: https://www.youtube.com/watch?v=KprFTxjQAoE

Electrical resistivity at low temperatures



Kelvin: Electrons will be frozen – resistivity grows till ∞.

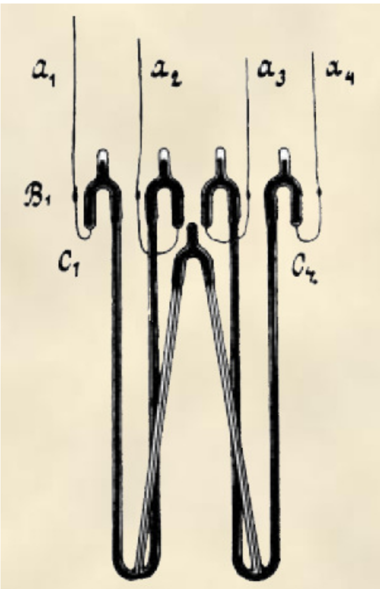
Dewar: the lattice will be frozen – the electrons will not be scattered. Resistivity wiil decrese till 0.

Matthiesen: Residual resistivity because of contamination and lattice defects.

One of the scientific challenge at the end of 19th and beginning of the 20th century: How to reach temperatures close to 0 K?

Hydrogen was liquefied (boiling point 20.28 K) for the first time by James Dewar in 1898

Discovery of Superconductivity



1895 William Ramsay in England discovered helium on the earth

1908 H. Kamerlingh Onnes liquefied helium (boiling point 4.22 K)

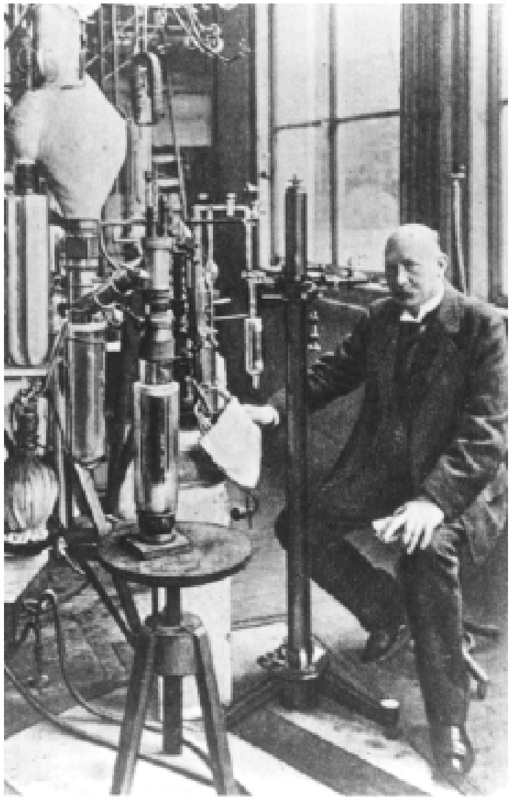
Resistivity at low temperatures- pure mercury (could repeatedly distilled producing very pure samples).

Repeated resistivity measurements indicated zero resistance at the liquid-helium temperatures. **Short circuit was assumed!**

During one repetitive experimental run, a young technician fall asleep. The helium pressure (kept below atmospheric one) slowly rose and, therefore, the boiling temperature. As it passed above 4.2 K, suddenly resistance appeared.

Hg T_C=4.2K

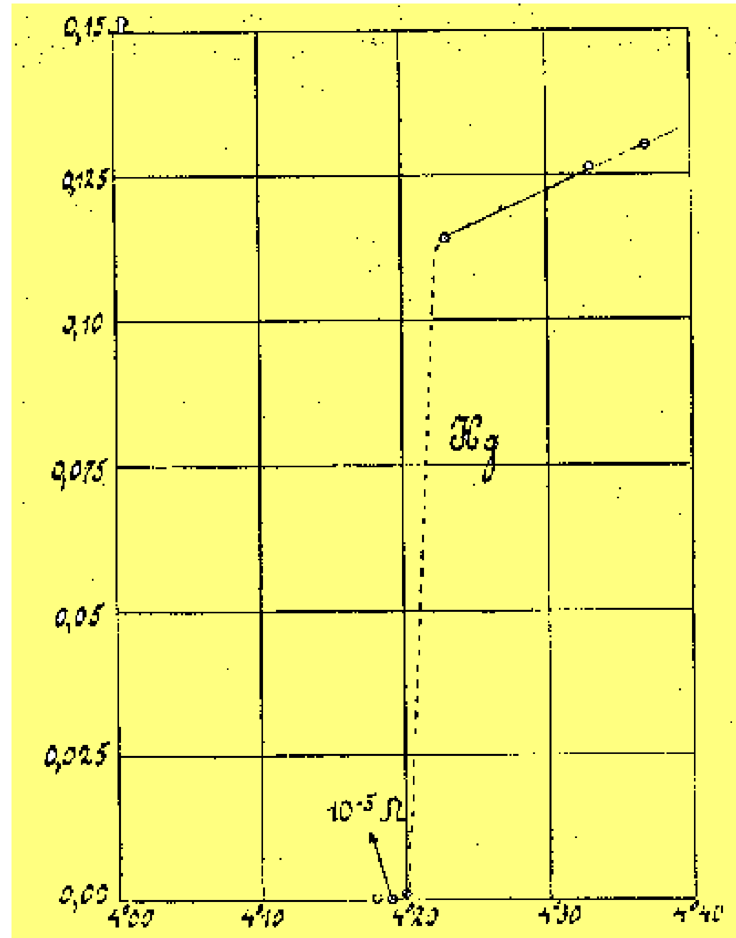
From: Rudolf de Bruyn Ouboter, "*Heike Kamerlingh Onnes's Discovery of Superconductivity*", Scientific American March 1997



Discovery of Superconductivity

Liquid Helium (4K) (1908). ***Boiling point*** 4.22K.

Superconductivity in Hg T_C=4.2K (1911)



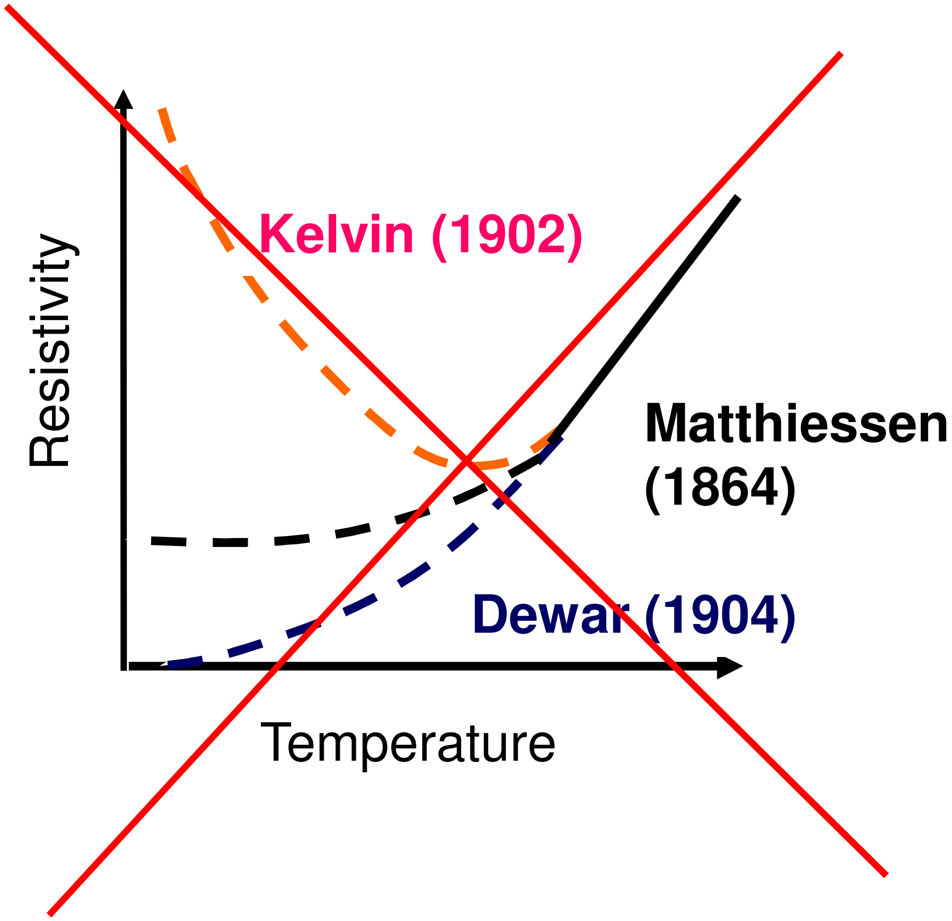
«Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconducting state»

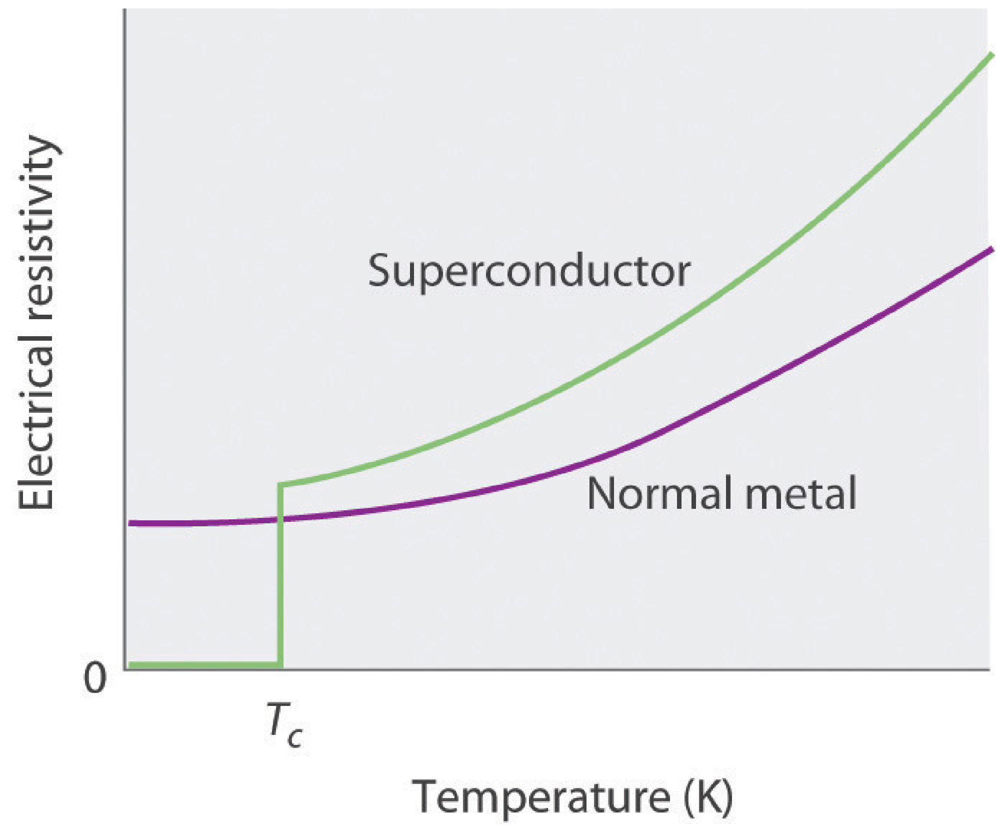
H. Kamerlingh Onnes

(Nobel prize 1913)

Resistivity R=0 below T_C; ($R<10^{-23}$ Ω·cm, 10^{18} times smaller than for Cu)

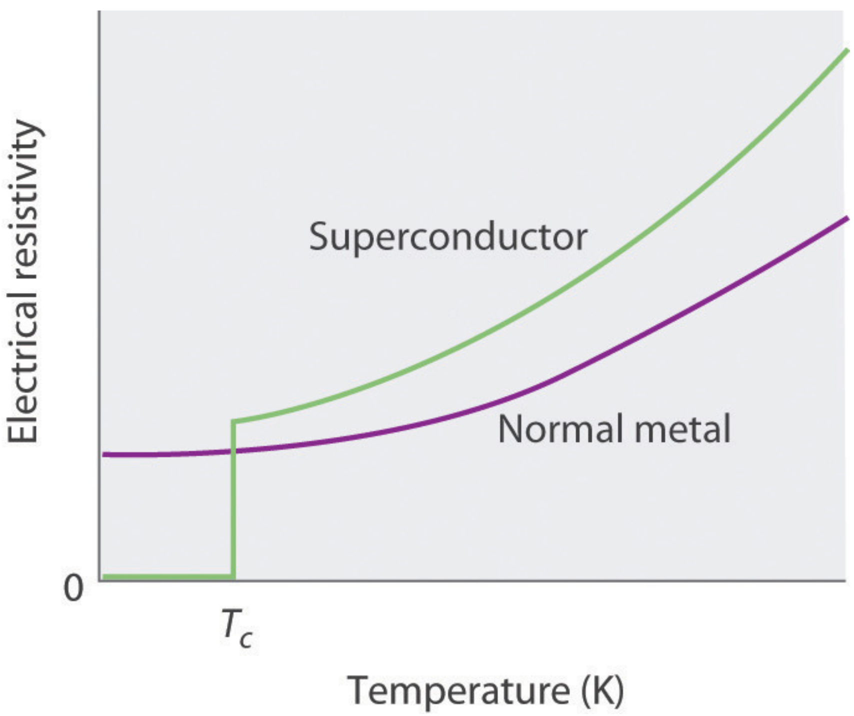
Superconductivity





Superconductivity

The electrical resistivity of a metallic conductor decreases gradually as the temperature is lowered. However, in ordinary conductors such as copper and silver, impurities and other defects impose a lower limit. Even near absolute zero a real sample of copper shows a non-zero resistance.



The resistance of a superconductor, on the other hand, drops abruptly to zero when the material is cooled below its "critical temperature", typically 20 kelvin or less.

An electrical current flowing in a loop of superconducting wire can persist indefinitely with no power source.

Superconductivity is a quantum mechanical phenomenon. It cannot be understood simply as the idealization of "perfect conductivity" in classical physics.

Superconductivity animation:
http://bestphysicsvideos.blogspot.com/2011/11/3-shorts-animations-about.html

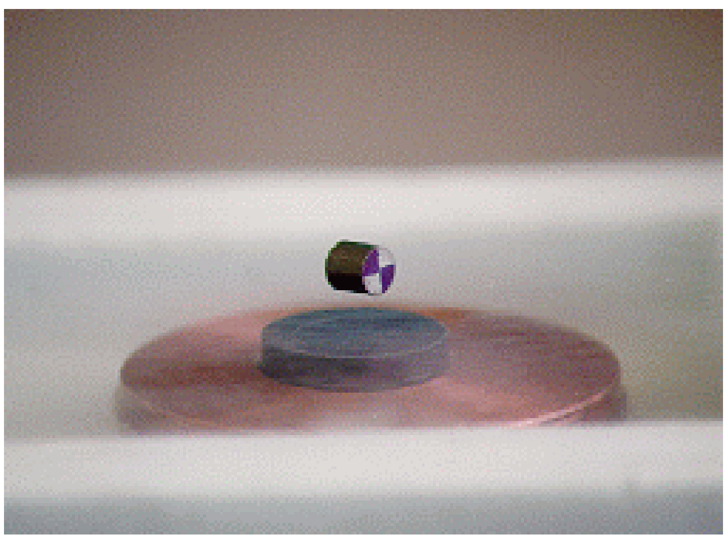
The current can flow 100 000 years!!

Meissner-Ochsenfeld-effect

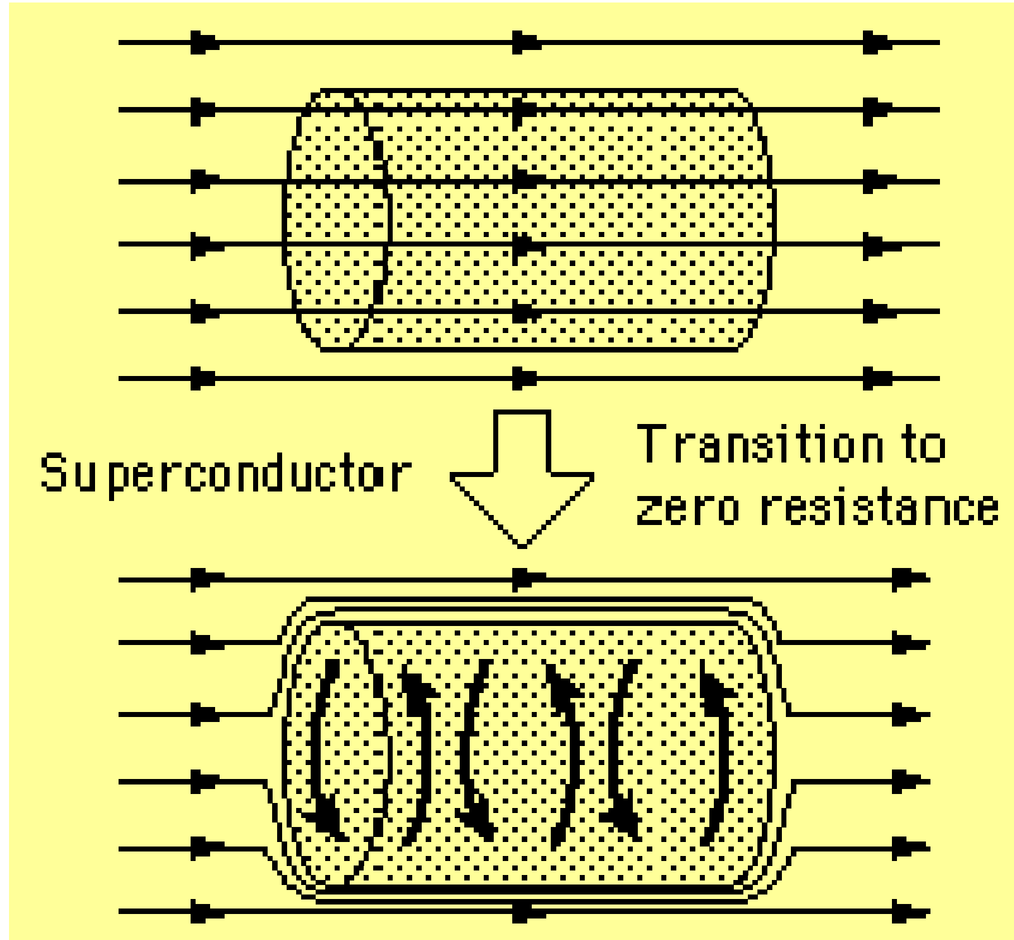
A superconductor is a perfect diamagnet. Superconducting material expels magnetic flux from the interior.

W. Meissner, R. Ochsenfeld (1933)

On the surface of a superconductor ($T<T_C$) superconducting current will be induced. This creates a magnetic field compensating the outside one.



Magnetic levitation



Screening (shielding) currents

Meissner-Ochsenfeld effect

Animation:
http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/levitation/

Description of the movie

The magnet is located on the superconductor: there is no interaction between them because the superconductor is above the critical temperature.

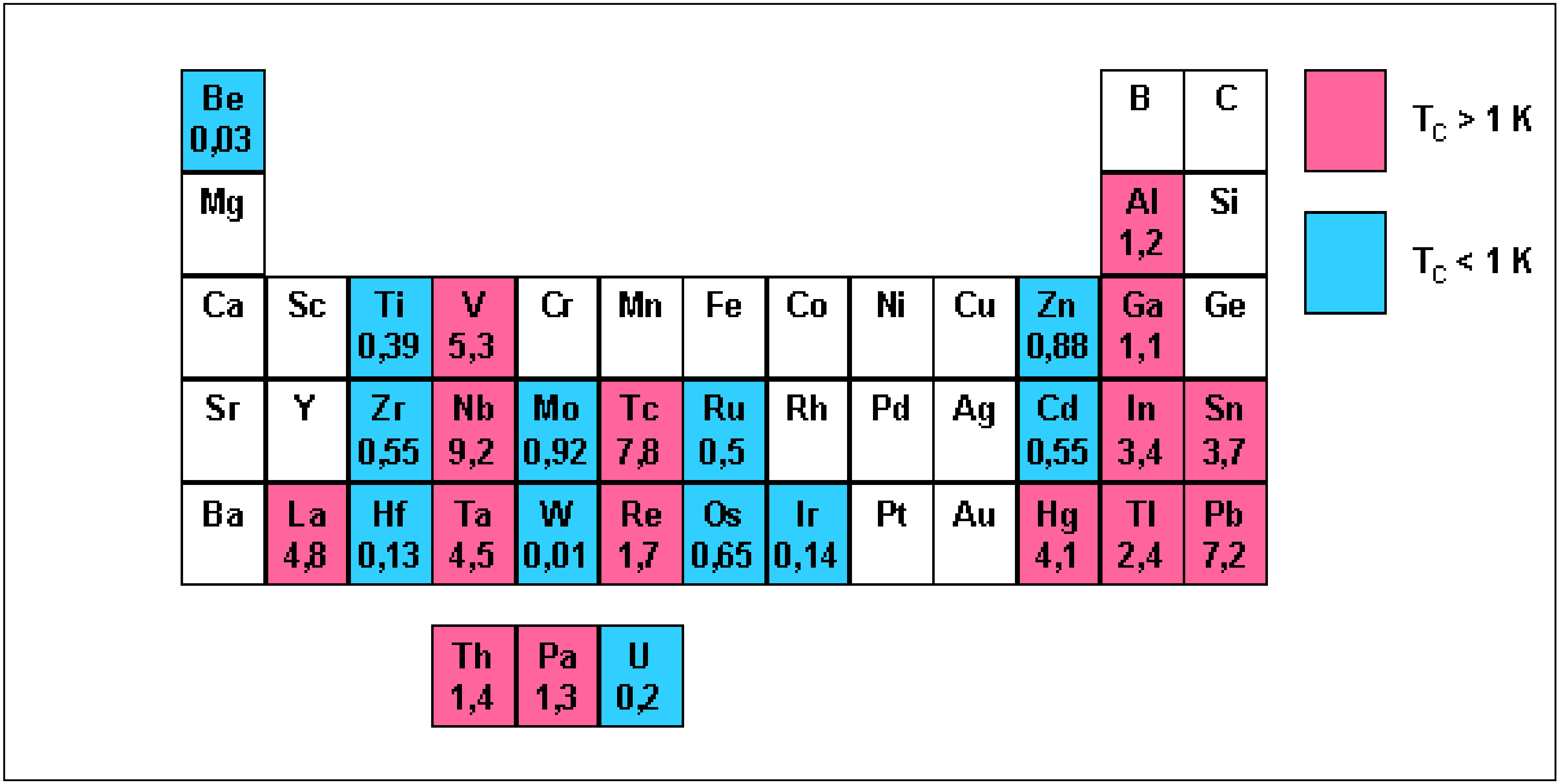
The magnet is placed on a glass plate so that its magnetic field penetrate the superconductor.

Pouring liquid nitrogen which has a temperature of 77 Kelvins (-196 Celsius). The cooling takes a few minutes.

The glass plate is removed but the magnet continues levitating above the superconductor.

After cooling by liquid nitrogen they get trapped by microscopic inhomogeneities in the superconductor. The trapped magnetic lines then serve as invisible threads holding the two objects together at a certain distance.

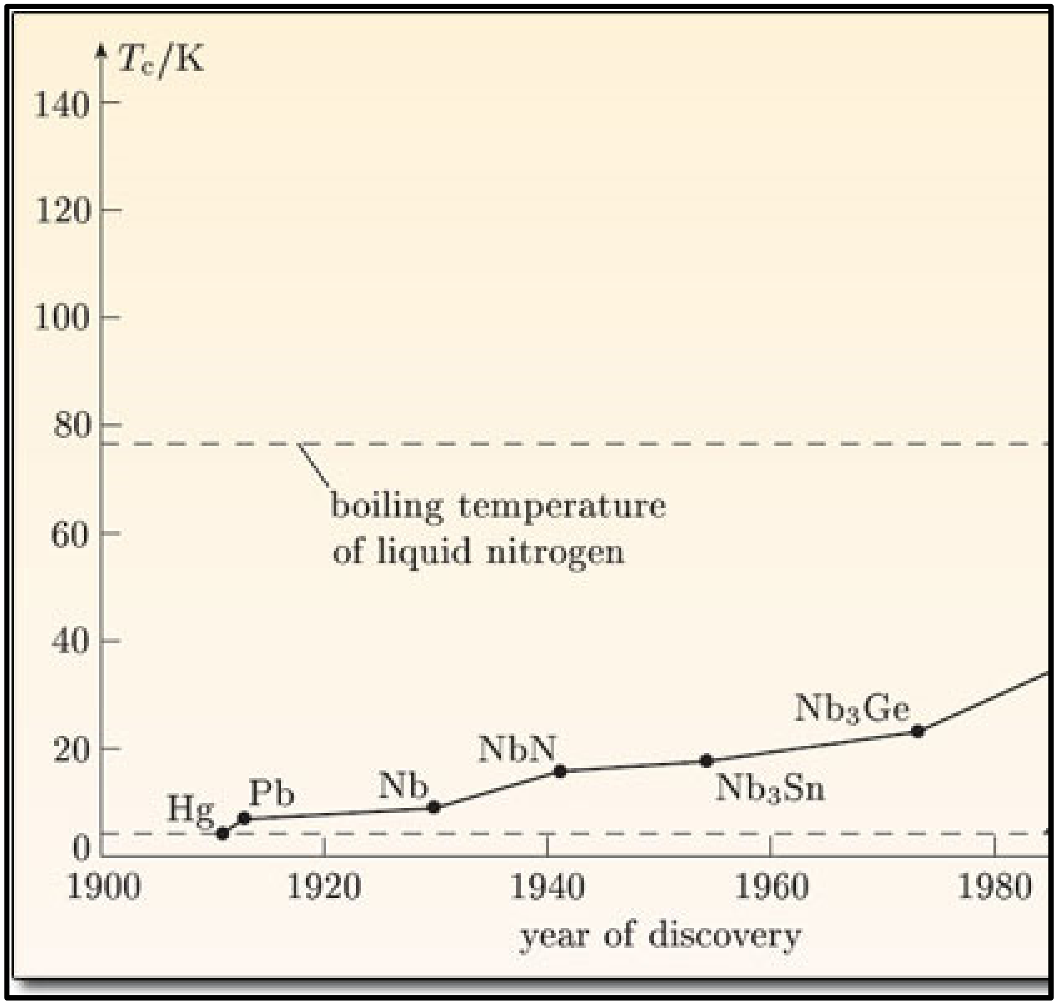
Superconducting elements



Ferromagnetic elements are not superconducting

The best conductors (Ag, Cu, Au..) are not superconducting

Nb has the highest T_C = 9.2K from all the elements



T_c/K
140
120
100
80
60
40
20
0
boiling temperature
of liquid nitrogen
Hg
Pb
Nb
NbN
Nb_3Sn
Nb_3Ge
1900
1920
1940
1960
1980
year of discovery

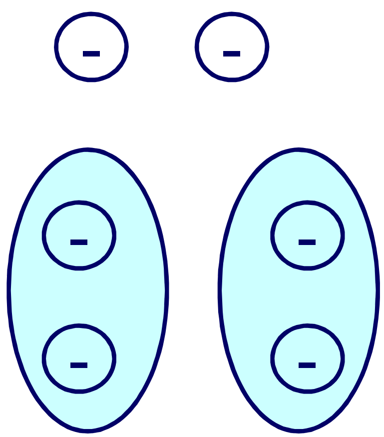
“Conventional” Superconductivity

BCS theory: 1957 John Bardeen, Leon Cooper, and John Robert Schrieffer

In a conventional superconductor, the electronic fluid cannot be resolved into individual electrons.

Instead, it consists of bound pairs of electrons known as Cooper pairs.

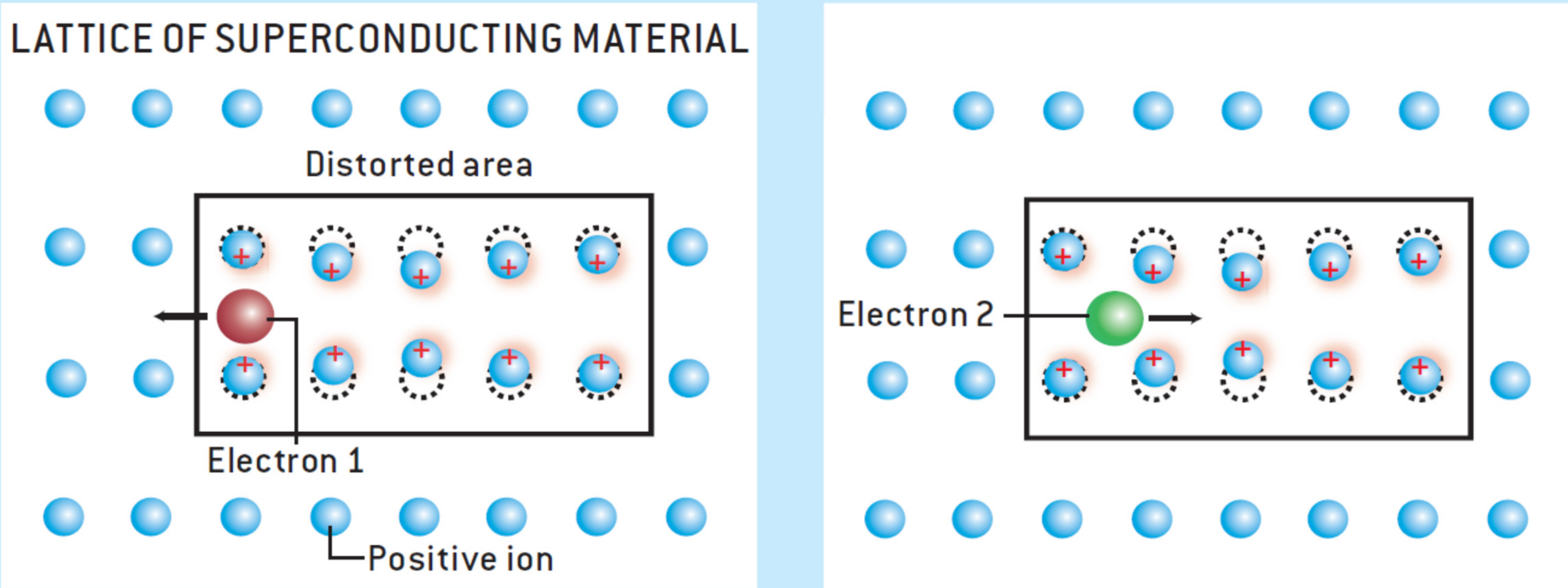
This pairing is caused by an attractive force between electrons from the exchange of phonons.



Singe electrons- the wave function is antisymmetric under exchange (FERMIONS)

Cooper pairs - the wave function is symmetric under exchange (BOSONS)

Cooper pairs

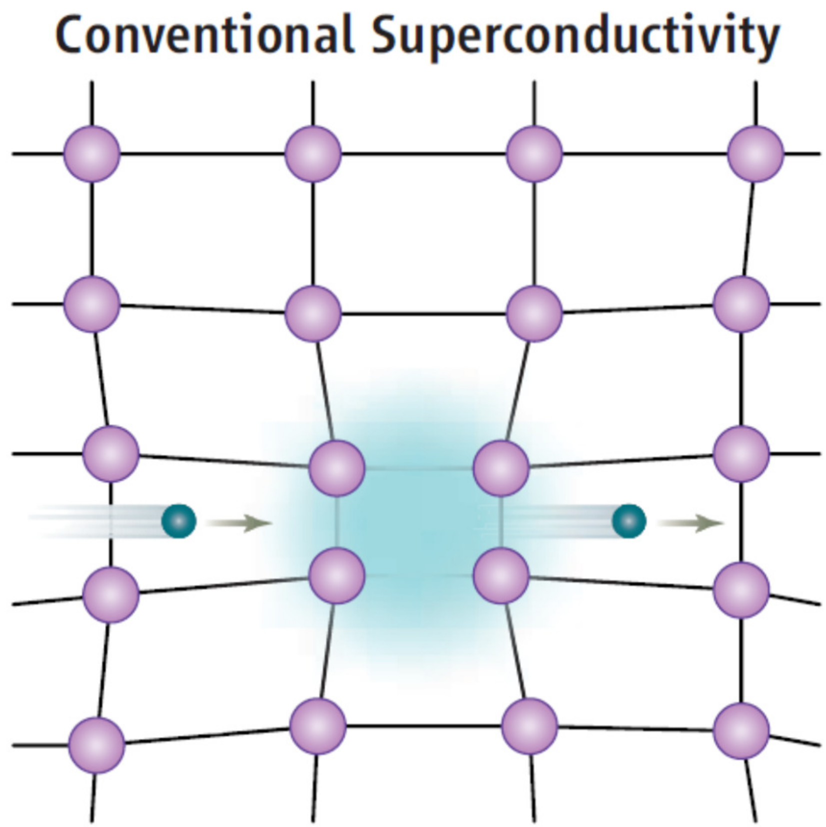


FORMATION OF ELECTRON PAIRS known as Cooper pairs (*above*) ultimately leads to superconductivity. One electron leaves in its wake a distortion of the lattice of positively charged ions in a metal (*left panel*). Shortly thereafter, the second electron is attracted by the resulting concentration of positive charge (*right panel*). In effect, the two electrons are weakly attracted to each other.

Superconductivity

Normally electrons do not form pairs as they repel each other. However, inside the material the electrons interact with ions of the crystal lattice.

Very simplify, the electron can interact with the positively charged background ions and create a local potential disturbance which can attract another electron.

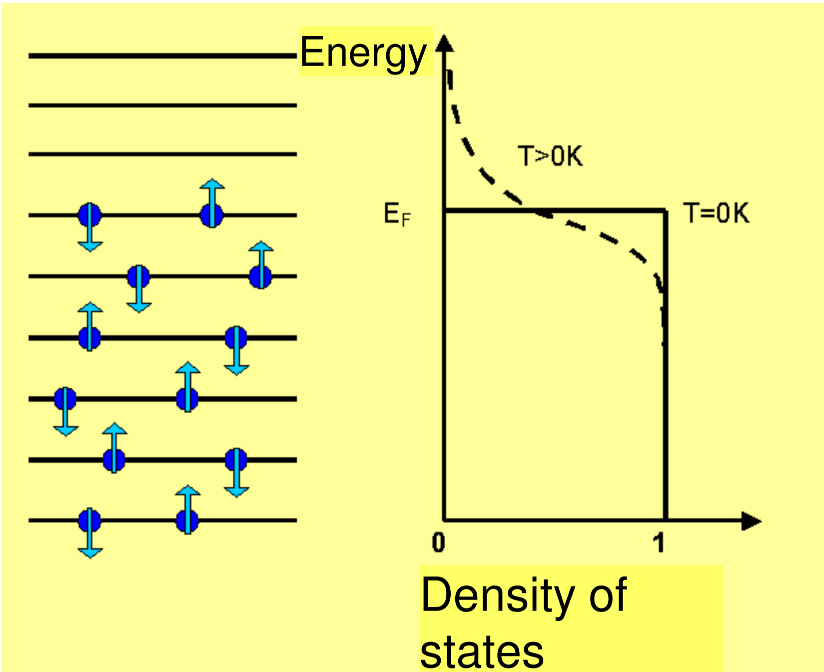


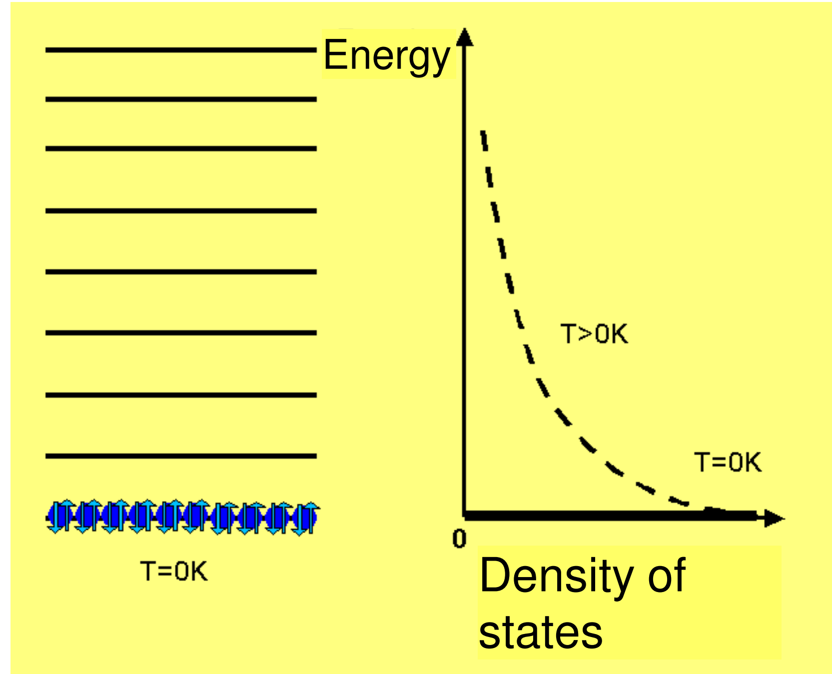
The binding energy of the two electrons is very small, 1meV, and the pairs dissociate at higher temperatures.

At low temperatures, the electrons can exists in the bound states (from Cooper pairs).

From BCS theory we learn that the lowest state of the system is the one in which Cooper pairs are formed.

Fermi and Bose-Statistic





Cooper-Pairs are created with electrons with opposite spins.

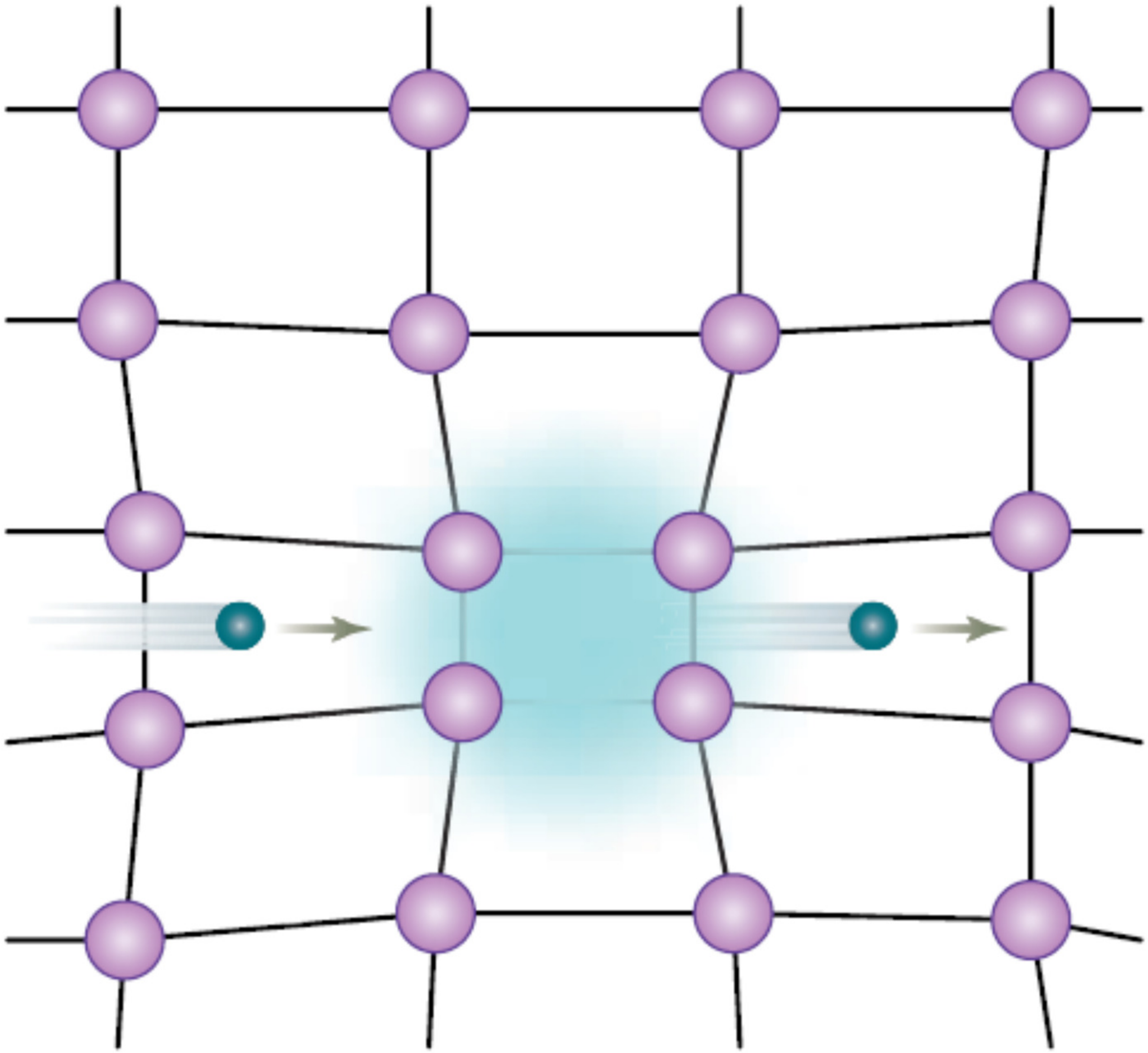
Fermions- elemental particles with 1/2 spin (e.g. electrons, protons, neutrons..)

Pauli-Principle –every energy level can be occupied with maximum two electrons with opposite spins.

Total spin of C-P is zero. C-P are **bosons**. Pauli-Principle doesn’t apply.

All Cooper pairs can have the same quantum state with the same energy.

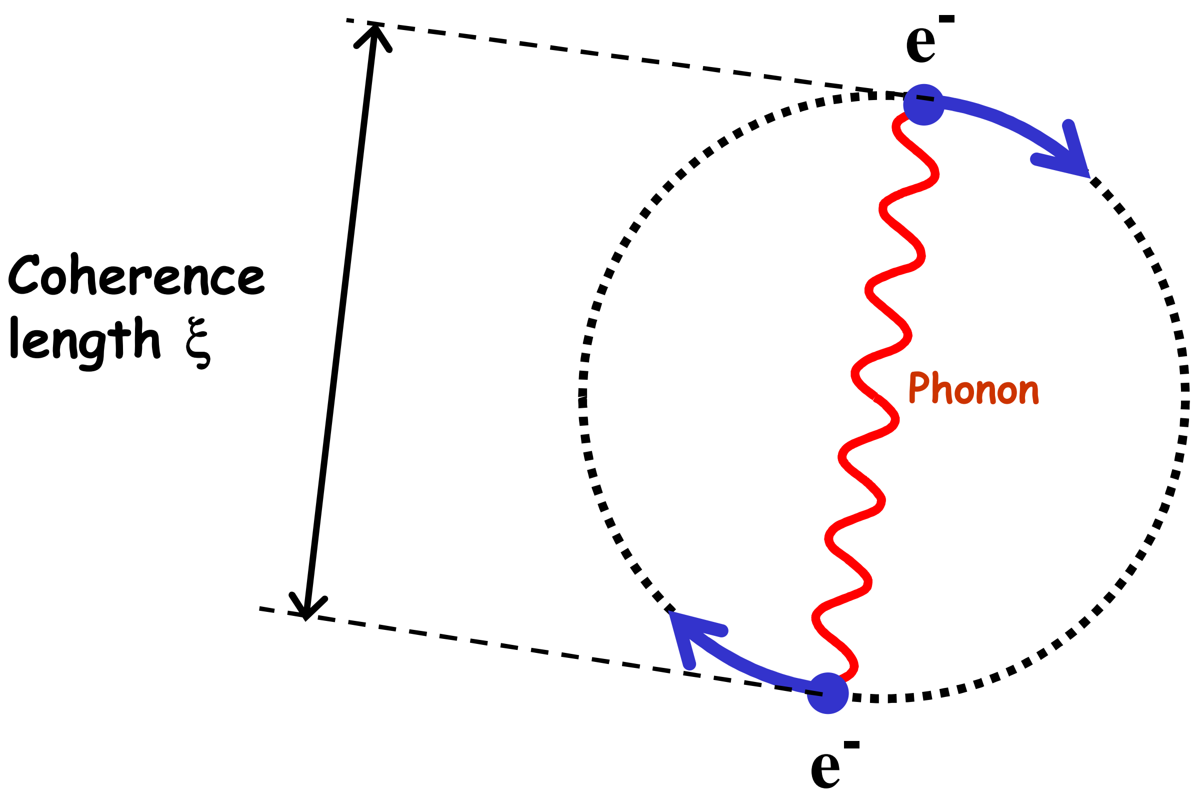
Conventional Superconductivity



http://bestphysicsvideos.blogspot.com/2011/11/3-shorts-animations-about.html

Nobel Prize in Physics 1972
"for their jointly developed theory of superconductivity, called the BCS-theory"

John Bardeen, Leon Neil Cooper, John Robert Schrieffer



Cooper pair model

Discovery of High Temperature Superconductivity

1911-1986: “Low temperature superconductors” Highest T_C=23K for Nb_3Ge

1986 (January): High Temperature Superconductivity $(LaBa)_2\ CuO_4$ T_C=35K

K.A. Müller und G. Bednorz (IBM Rüschlikon) (Nobel prize 1987)

1987 (January): $YBa_2Cu_3O_{7-x}$ T_C=93K

1987 (December): Bi-Sr-Ca-Cu-O T_C=110K

1988 (January): Tl-Ba-Ca-Cu-O T_C=125K

1993: Hg-Ba-Ca-Cu-O T_C=133K

(A. Schilling, H. Ott, ETH Zürich)

Professor Dr. Dr. h. c. mult. Karl Alex Müller (links) und Dr. Johannes Georg Bednorz

Z. Phys. B – Condensed Matter 64, 189–193 (1986)

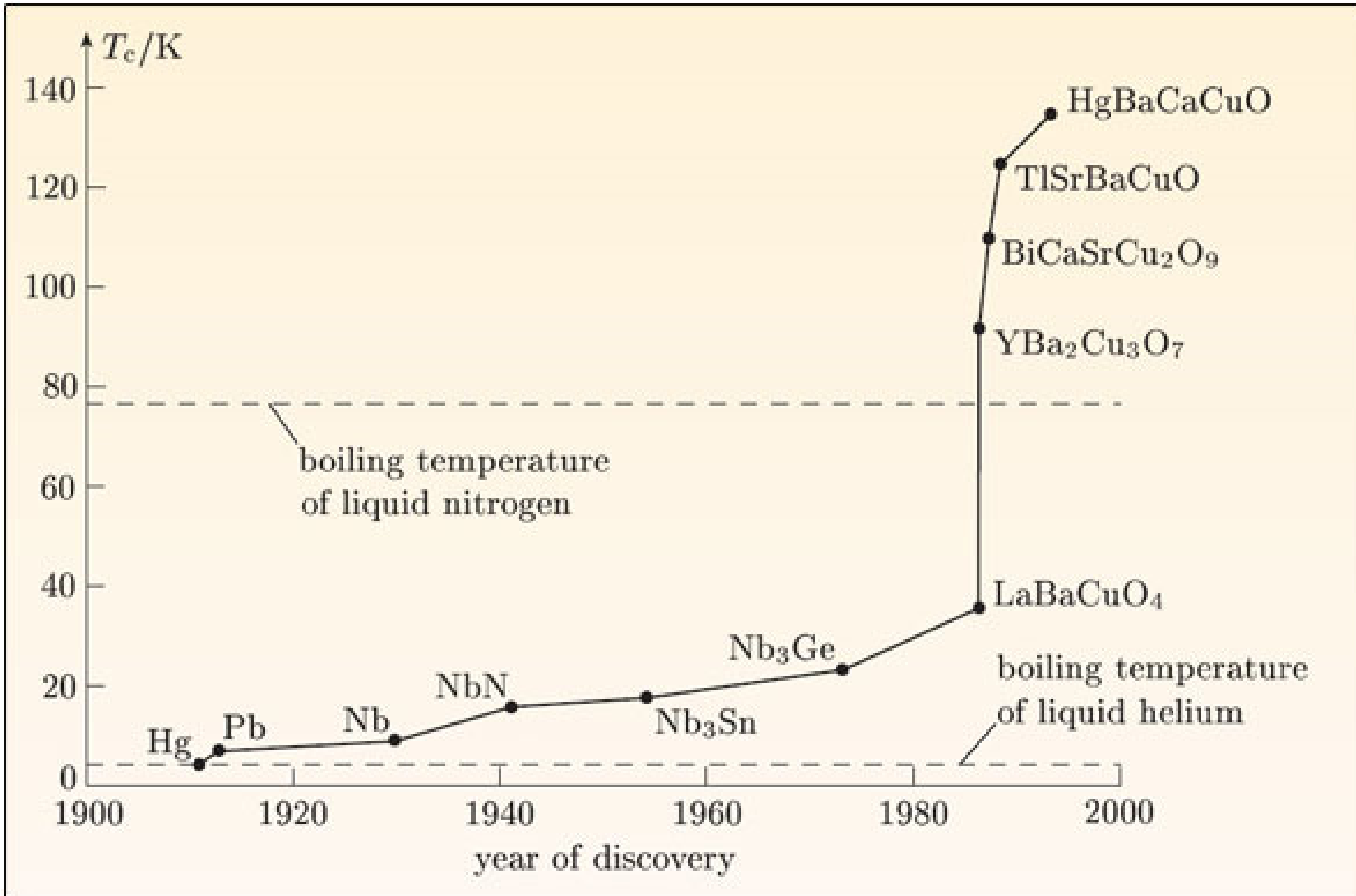
Zeitschrift für Physik B Condensed Matter

Possible High T_c Superconductivity in the Ba – La – Cu – O System

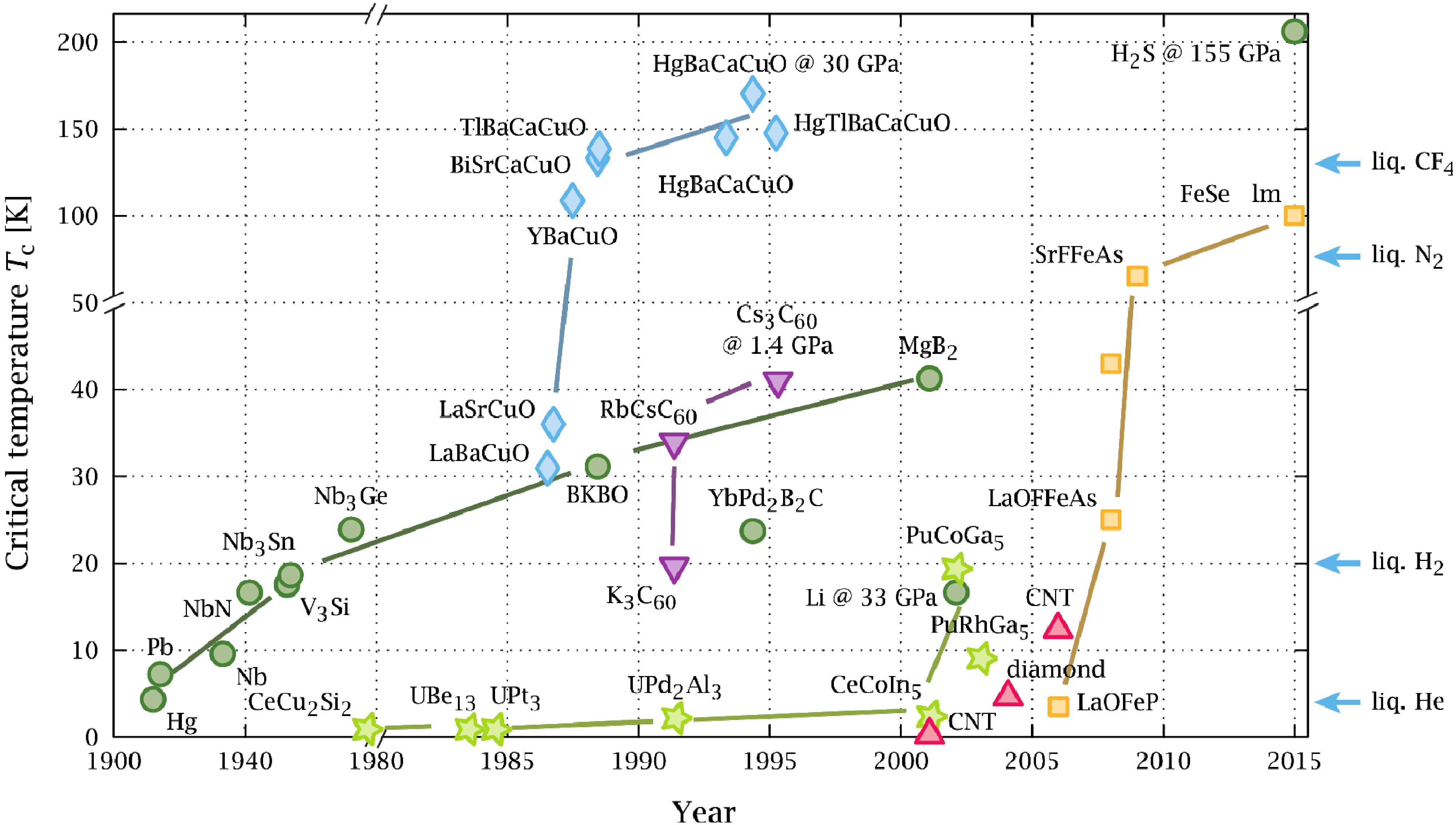
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

Metallic, oxygen-deficient compounds in the Ba – La – Cu – O system, with the composition $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, bute possibly also from $2D$ superconducting fluctuations of double perovskite layers of one of the phases present.



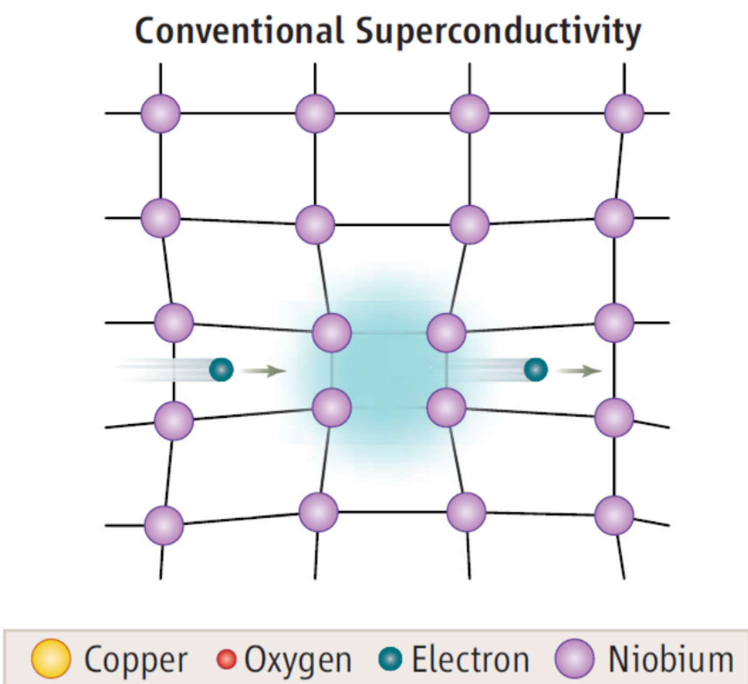
T_c/K
140
120
100
80
60
40
20
0
1900
1920
1940
1960
1980
2000
year of discovery
Hg
Pb
Nb
NbN
Nb_3Sn
Nb_3Ge
$LaBaCuO_4$
$YBa_2Cu_3O_7$
$BiCaSrCu_2O_9$
TlSrBaCuO
HgBaCaCuO
boiling temperature of liquid nitrogen
boiling temperature of liquid helium

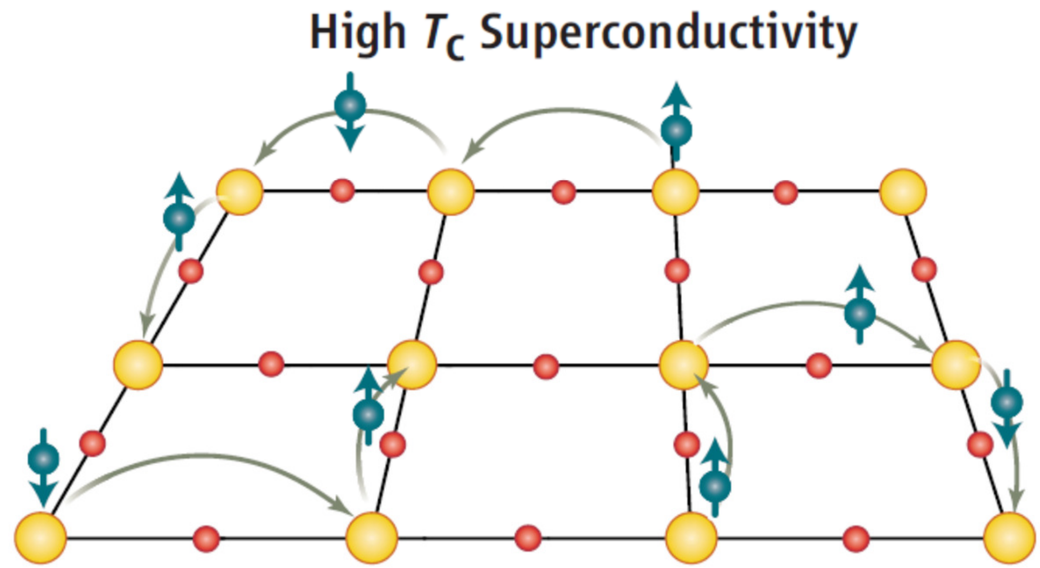


Critical temperature T_c [K]
Year
HgBaCaCuO @ 30 GPa
TlBaCaCuO
HgTlBaCaCuO
BiSrCaCuO
HgBaCaCuO
YBaCuO
H$_2$S @ 155 GPa
FeSe lm
SrFFeAs
liq. CF$_4$
liq. N$_2$
liq. H$_2$
liq. He
Cs$_3$C$_{60}$ @ 1.4 GPa
MgB$_2$
LaSrCuO
RbCsC$_{60}$
LaBaCuO
BKBO
Nb$_3$Ge
YbPd$_2$B$_2$C
LaOFFeAs
Nb$_3$Sn
PuCoGa$_5$
K$_3$C$_{60}$
Li @ 33 GPa
NbN
V$_3$Si
CNT
PuRhGa$_5$
Pb
Nb
diamond
CeCu$_2$Si$_2$
UBe$_{13}$
UPt$_3$
UPd$_2$Al$_3$
CeCoIn$_5$
LaOFeP
Hg
CNT

After 2 decades of monumental effort, physicists still cannot explain high-temperature superconductivity. But they may have identified the puzzles they have yet to solve

High T_C: The Mystery That Defies Solution



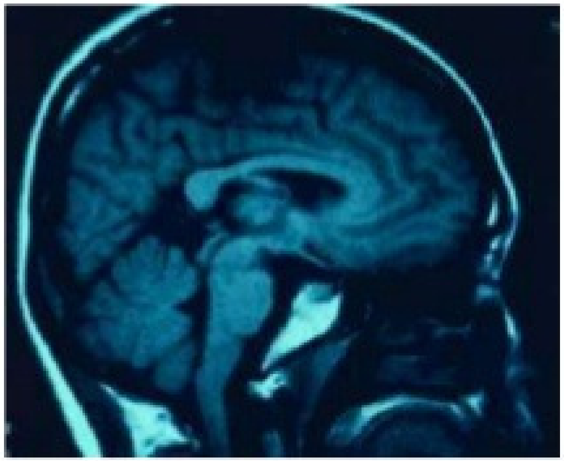


Shall we dance? Instead of the motion of ions, the subtle waltz of electrons along atomic planes may cause pairing in high-temperature materials.

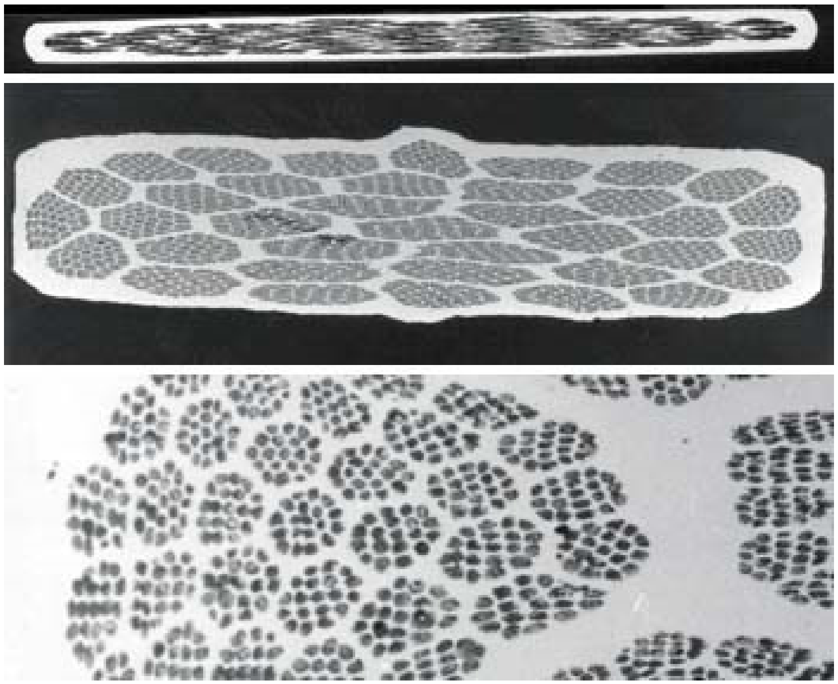
Applications of Superconductors

- •Particle Accelerators
- •Generators
- •Transportation
- •Power Transmission
- •Electric Motors
- •Military
- •Computing
- •Medical
- •B Field Detection (SQUIDS)

The Yamanashi MLX01 MagLev train

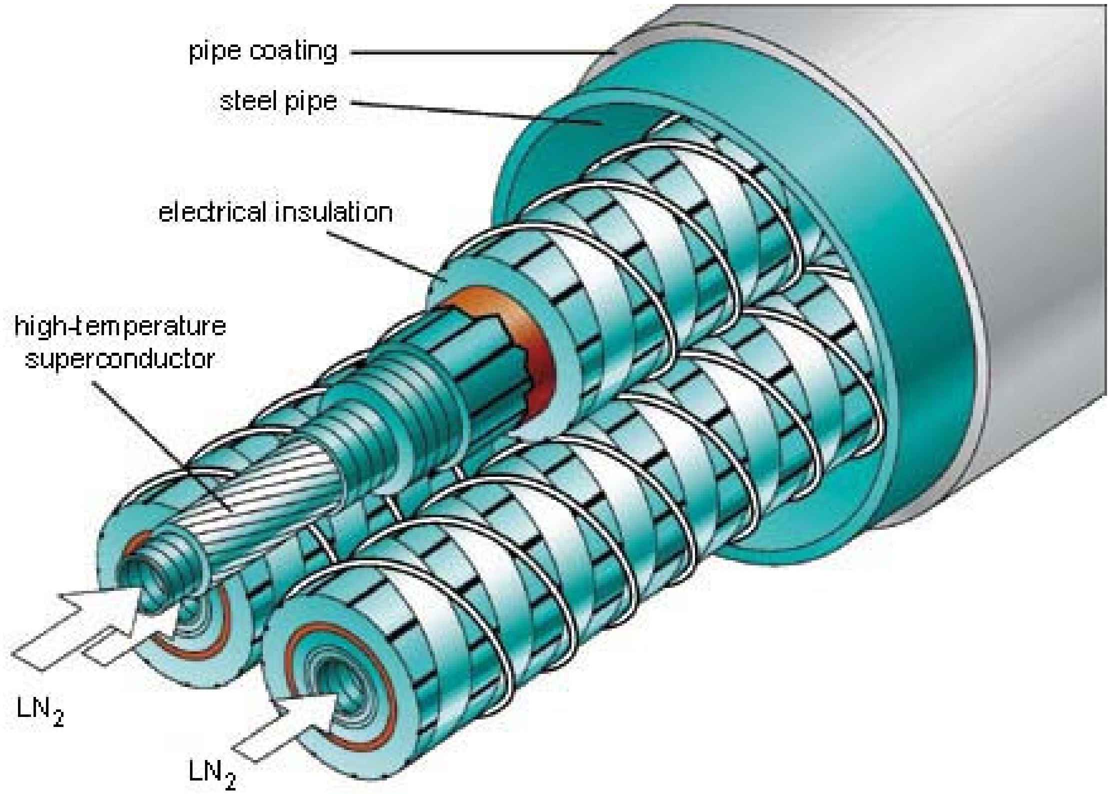


Applications. Wires and bands.



Cross section of HT_C band

American Superconductor Corporation



HT_C Cable

Superconducting Wires and Applications

ORNL High-Temperature Superconductivity Program

Office of Electricity Delivery and Energy Reliability

Develop high-performance low-cost high-temperature superconducting (HTS) wires in long lengths

Demonstrate compact highly efficient HTS applications

HTS Wires

Flexible "single crystals" by the kilometer

Integrate metallurgy, semiconductor- and nano-technologies

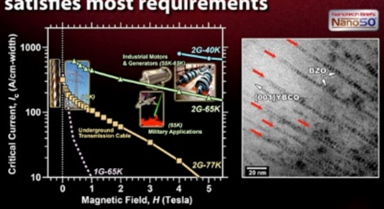
ORNL Template

Textured Templates

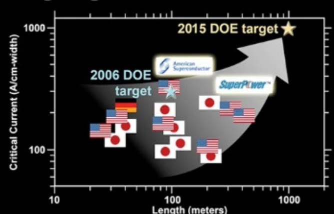
World Class Performance

Utilize nano-defect engineering & materials by design

Lab-scale wire with aligned nanodots satisfies most requirements



Long length wires set World Records



Superconducting Electric Power Equipment

Half the energy losses, half the size and lower operating costs compared to conventional units

Columbus Triaxial HTS Cable

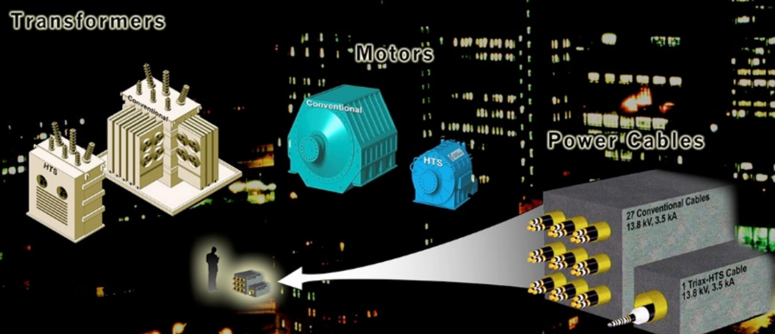
- **World Records:**
  Most compact,
  Highest current density,
  Lowest cost design

HTS Transformers

- **No oil to ignite**
- **Urban siting**

HTS Motors

- **Weight redistribution**
- **Efficient & stable**

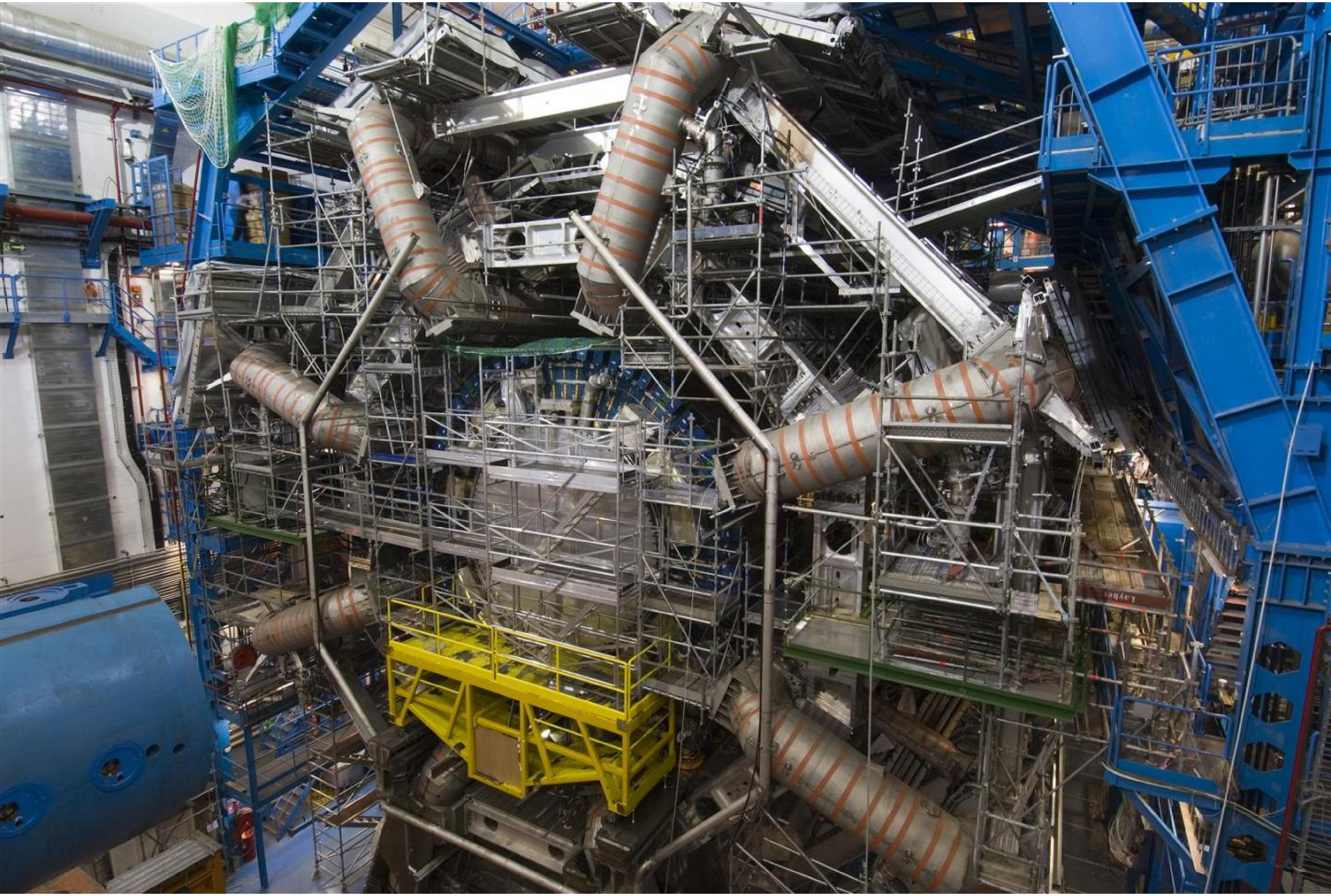


HTS Fault Current Limiters

- **Fail-safe operations**
- **Better power quality**

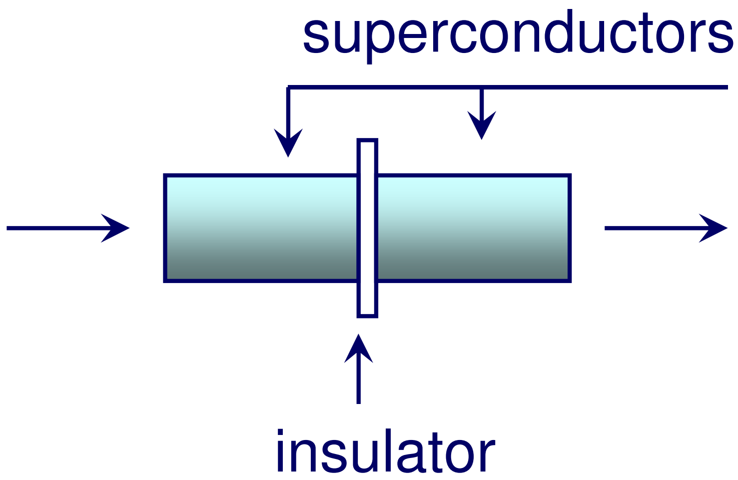
Contact
Dominic Lee
(865) 241-0775
leedf@ornl.gov
www.ornl.gov/sci/htsc/hstc.html

OAK RIDGE NATIONAL LABORATORY



The magnet system on the ATLAS detector includes eight huge superconducting magnets (grey tubes) arranged in a torus around the LHC beam pipe (Image: CERN)

Josephson junction



$$J = J_0 \sin\delta$$

Josephson junction:
a thin insulator sandwiched
between two superconductors

phase difference $\delta = \theta_2 - \theta_1$

Depends on the tunneling probability of the electron pairs

There is a current flow across the junction in the absence of an applied voltage!

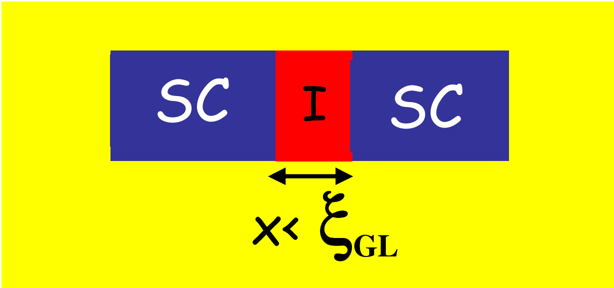
Nobel Prize in Physics 1973

"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".

Brian David Josephson

Josephson discovered in 1963 tunnelling effect being 23-years old PhD student

The **superconducting tunnel Josephson junction**— is an electronic device consisting of two superconductors separated by a very thin layer of insulating material



Superconducting devices

Extremely interesting devices may be designed with a superconducting loop with two arms being formed by Josephson junctions.

The operation of such devices is based on the fact that the phase difference around the closed superconducting loop which encloses the magnetic flux Φ is an integral product of $2e\Phi/\hbar$.

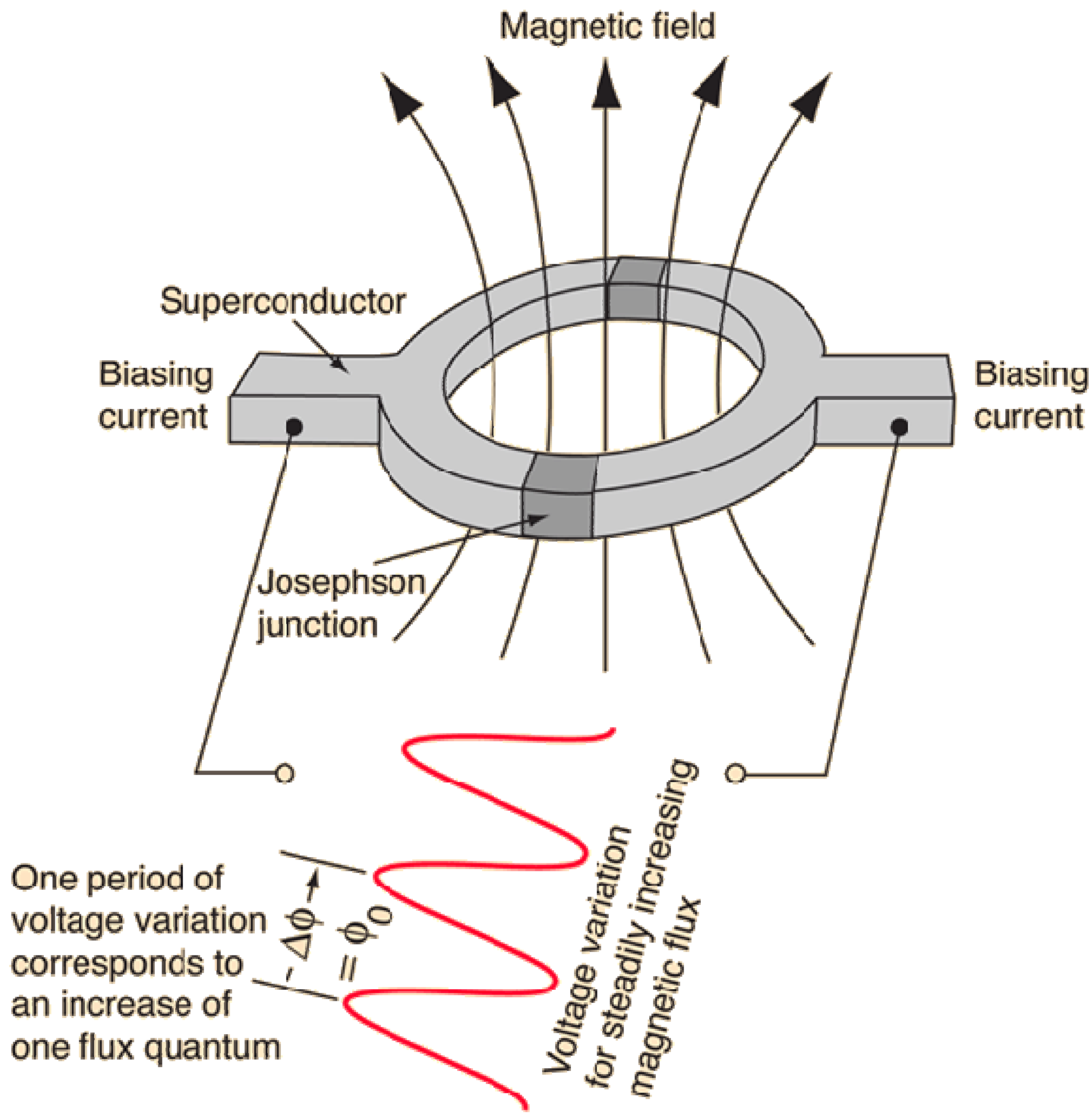
The current will vary with Φ and has maxima at $\dfrac{e\Phi}{\hbar} = n\pi$.

The control of the current through the superconducting loop is the basis for many important devices. Such loops may be used in production of low power digital logic devices, detectors, signal processing devices, and extremely sensitive magnetic field measurement instruments .

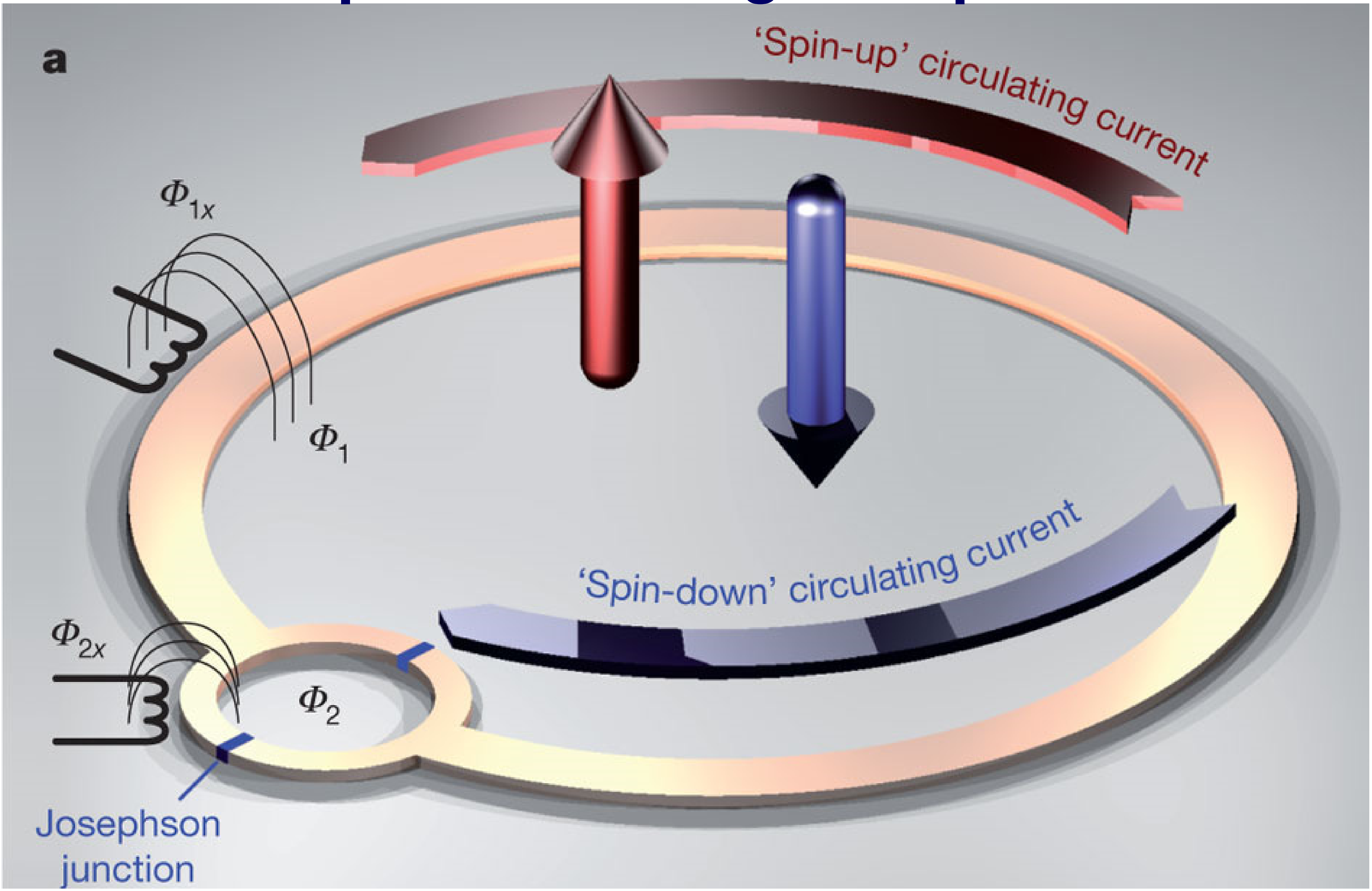
SQUID magnetometer (Superconductind QUantum Interference Device)

SQUID magnetometer (Superconductind QUantum Interference Device)

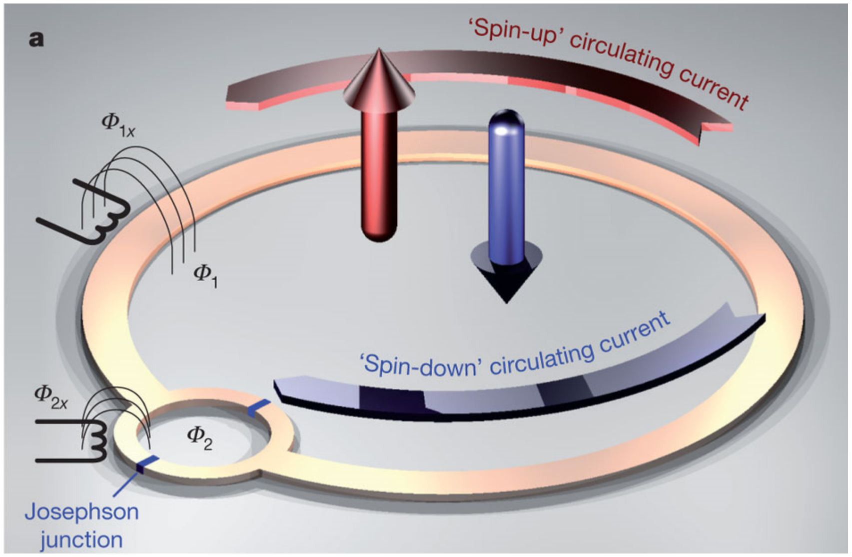
The great sensitivity of the SQUID devices is associated with measuring changes in magnetic field associated with one flux quantum.



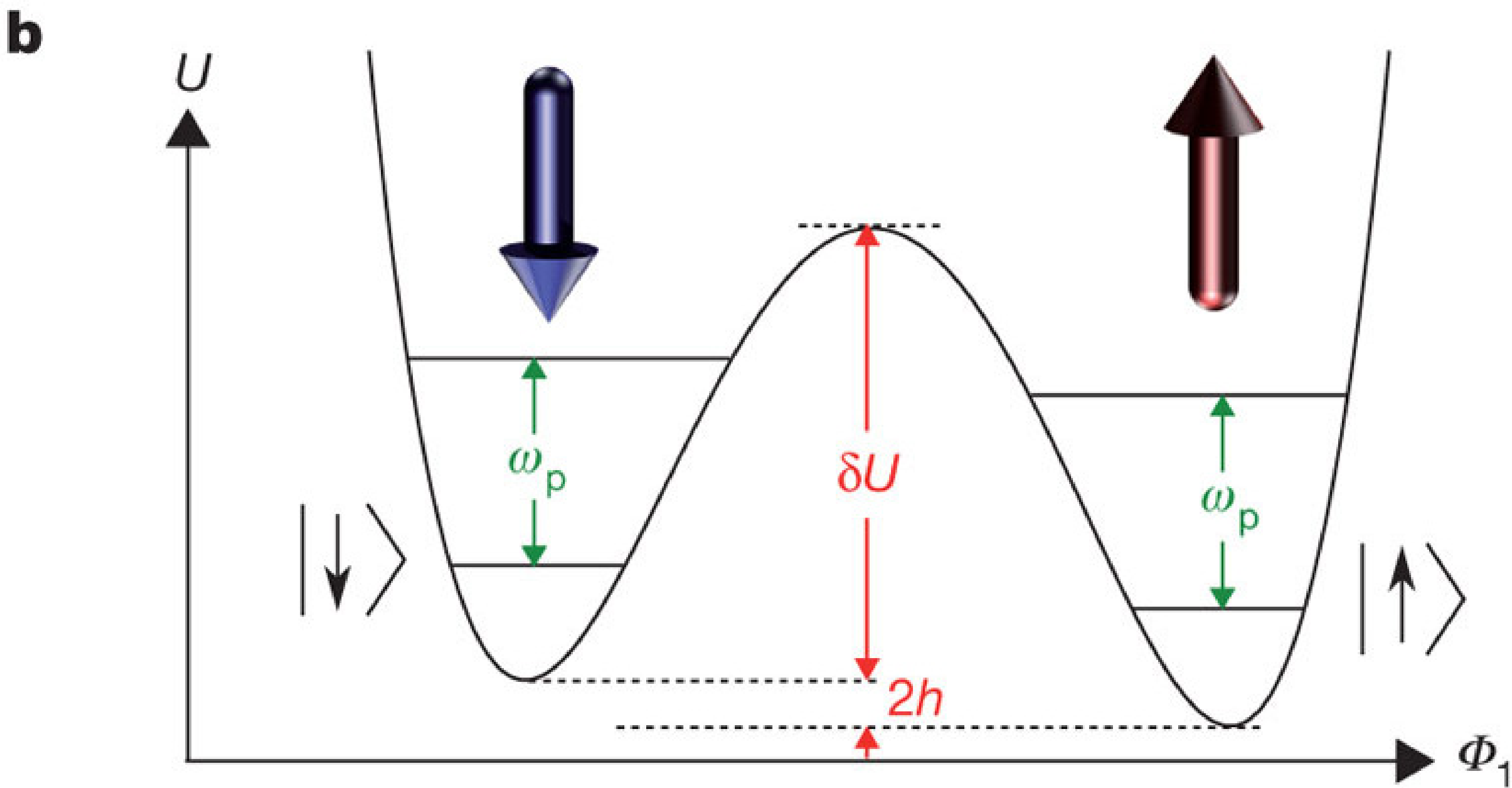
Superconducting flux qubit

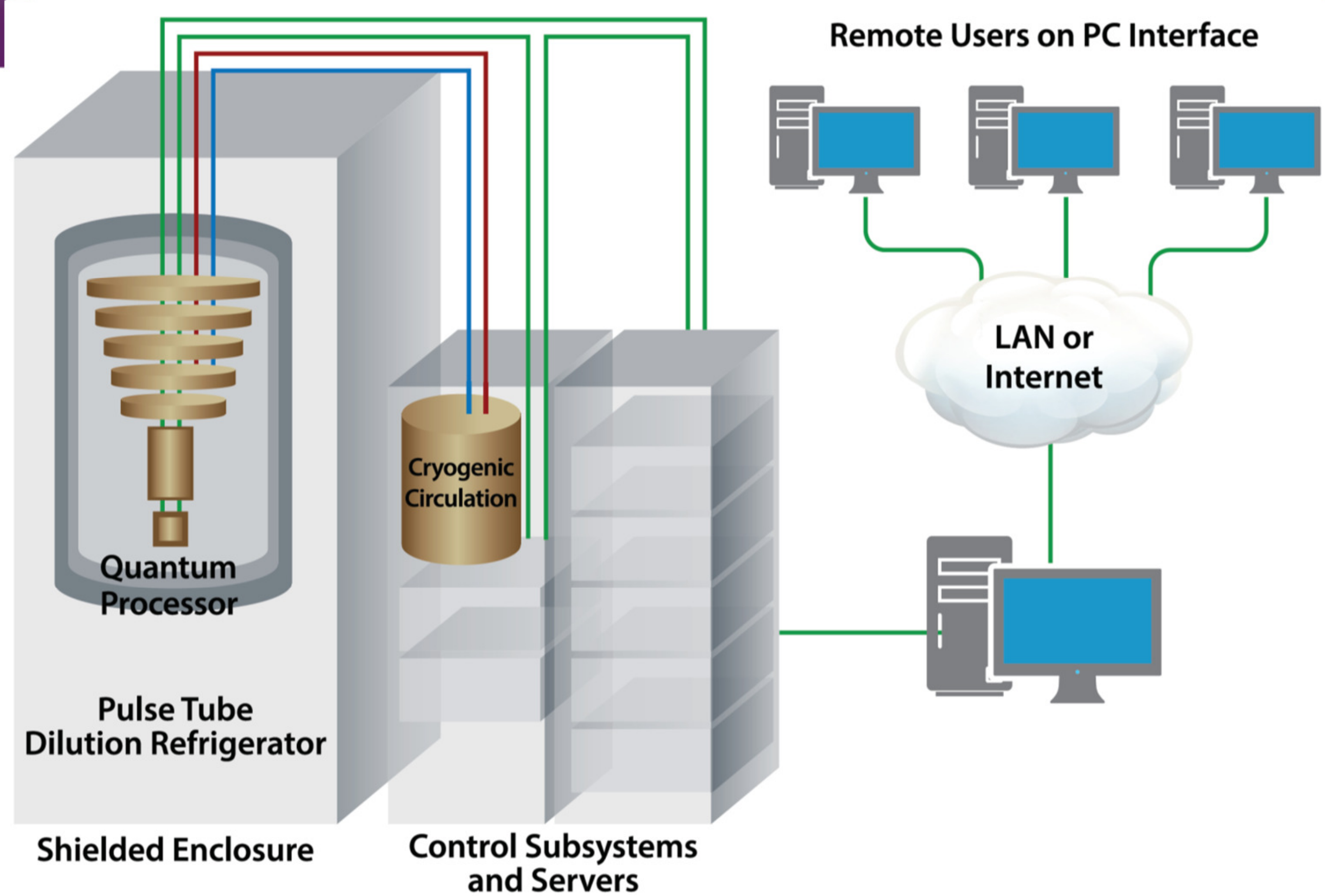


MW Johnson *et al.* *Nature* **473**, 194-198 (2011) doi:10.1038/nature10012



Double-well potential energy diagram and the lowest quantum energy levels corresponding to the qubit. States ↑ and ↓ are the lowest two levels, respectively.





http://www.dwavesys.com/

COMPUTER SCIENCE

Quantum or not, controversial computer yields no speedup

Conventional computer ties D-Wave machine

SCIENCE 20 JUNE 2014 • VOL 344 ISSUE 6190