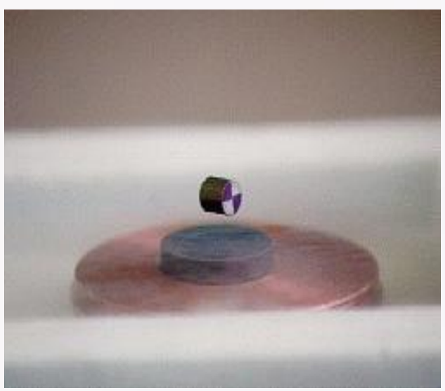
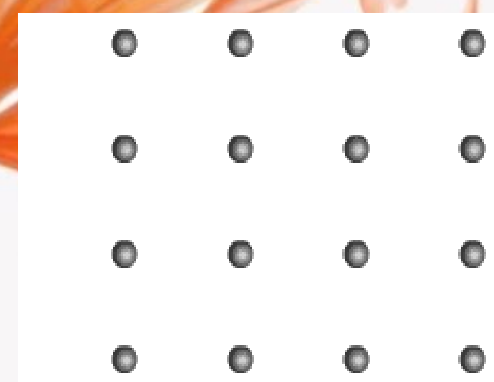
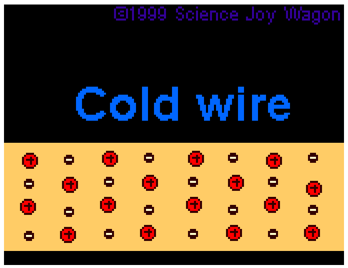
Superconductivity



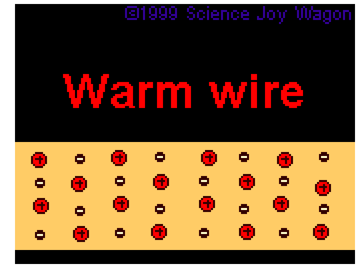


S. ARUMUGAM
Centre for High Pressure Research
Bharathidasan University, Tiruchirappalli-24

Temperature Dependence of Resistance



Electrical Resistivity
$\rho = \rho_o + \rho(T)$
- Impurities
- Phonons



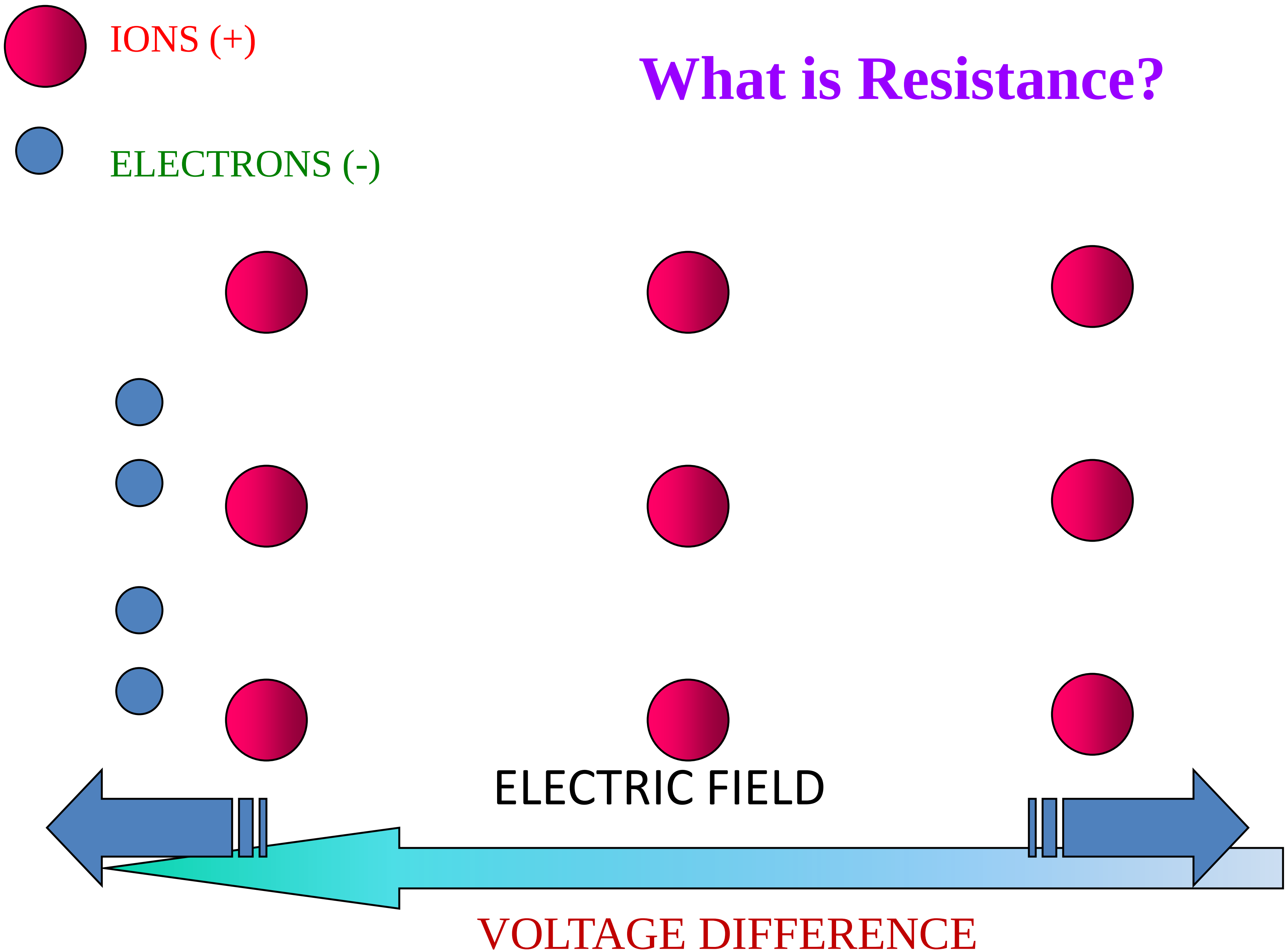
High Temperature

- **Impure Metals**
  $\rho = \rho_o + \rho(T)$
- **Pure Metals**
  $\rho = \rho(T)$

Low Temperature

- **Impure Metals**
  $\rho = \rho_o$
- **Pure Metals**
  $\rho = 0$
  Superconductor

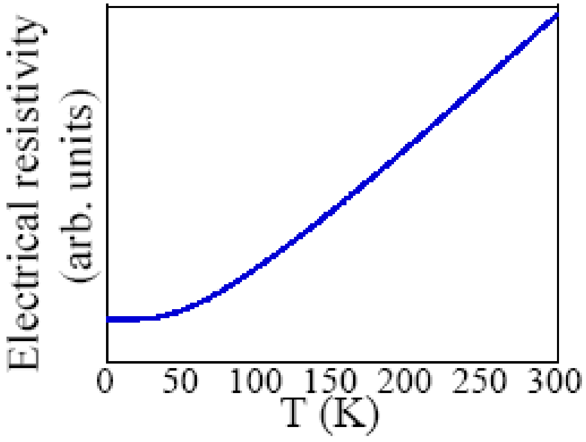
What is Resistance?



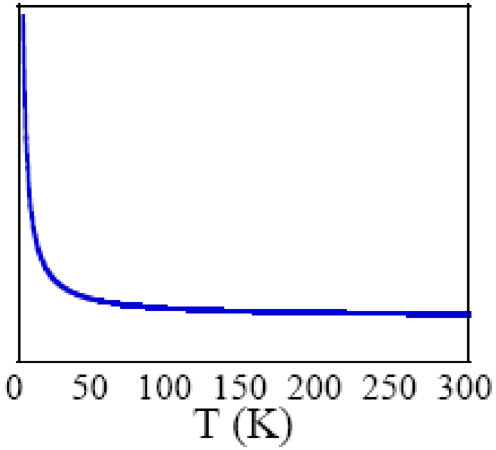
Electrical resistivity of three states of solid matter

- **Graphite is a metal, diamond is an insulator and buckminster-fullerene is a superconductor.**

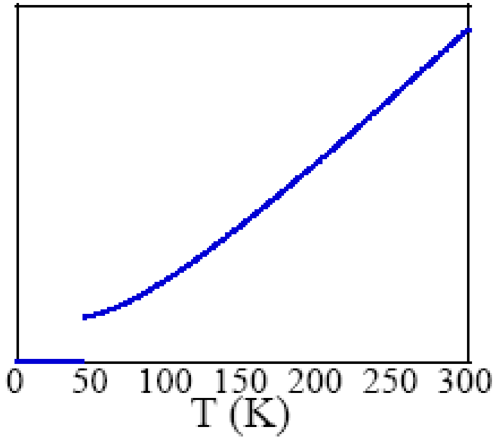
They are all just carbon!



Metal



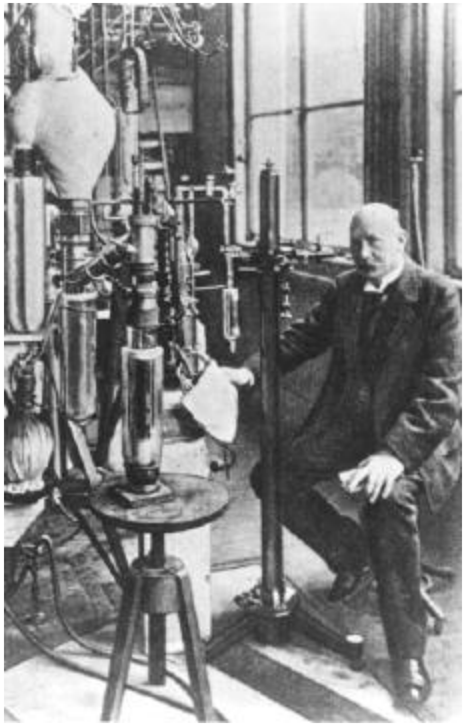
Insulator



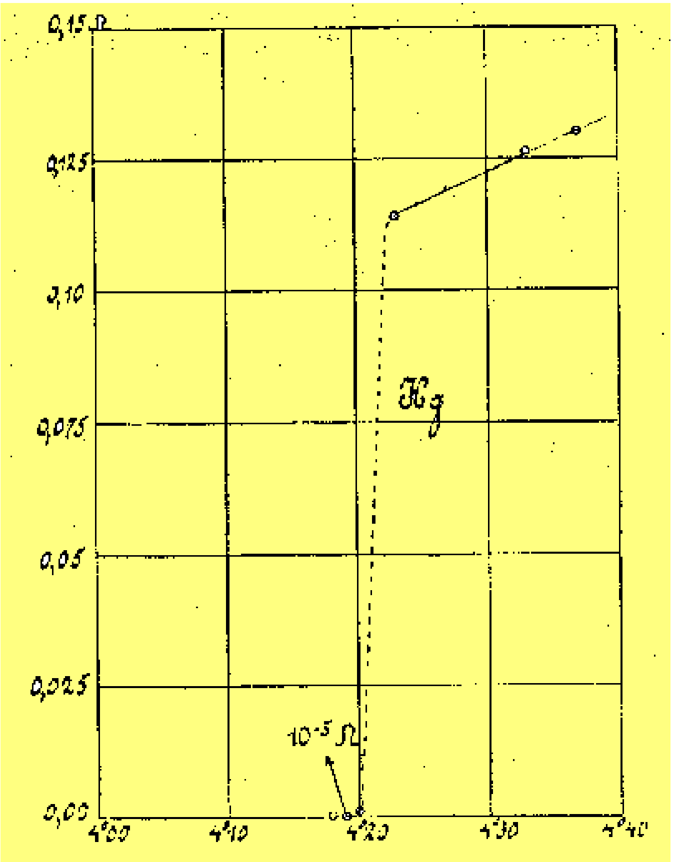
Superconductor

Introduction

Superconductivity- discovery



- Liquid Helium (4K) (1908). ***Boiling point*** 4.22K.
- Superconductivity in Hg T_C=4.2K (1911)



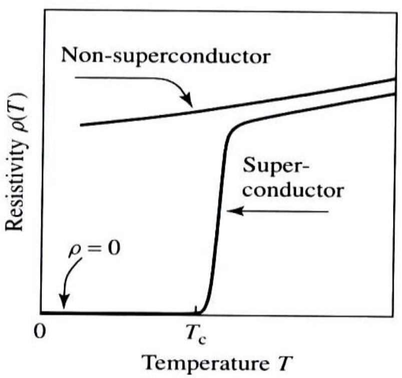
„Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconducting state“

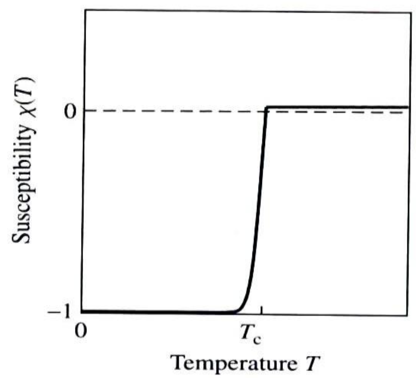
H. Kamerlingh Onnes 1911 (Nobel prize 1913)

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

Introduction..

What is Superconductivity??





✓ Superconductivity is the ability of certain materials to conduct electrical current with no resistance.

✓ Thus, superconductors can carry large amounts of current with little or no loss of energy.

$Q = I^2.R = 0$ (R = 0)

$V = I.R$ or $V/I = R = 0$ (R =0)

W. Meissner (1933)

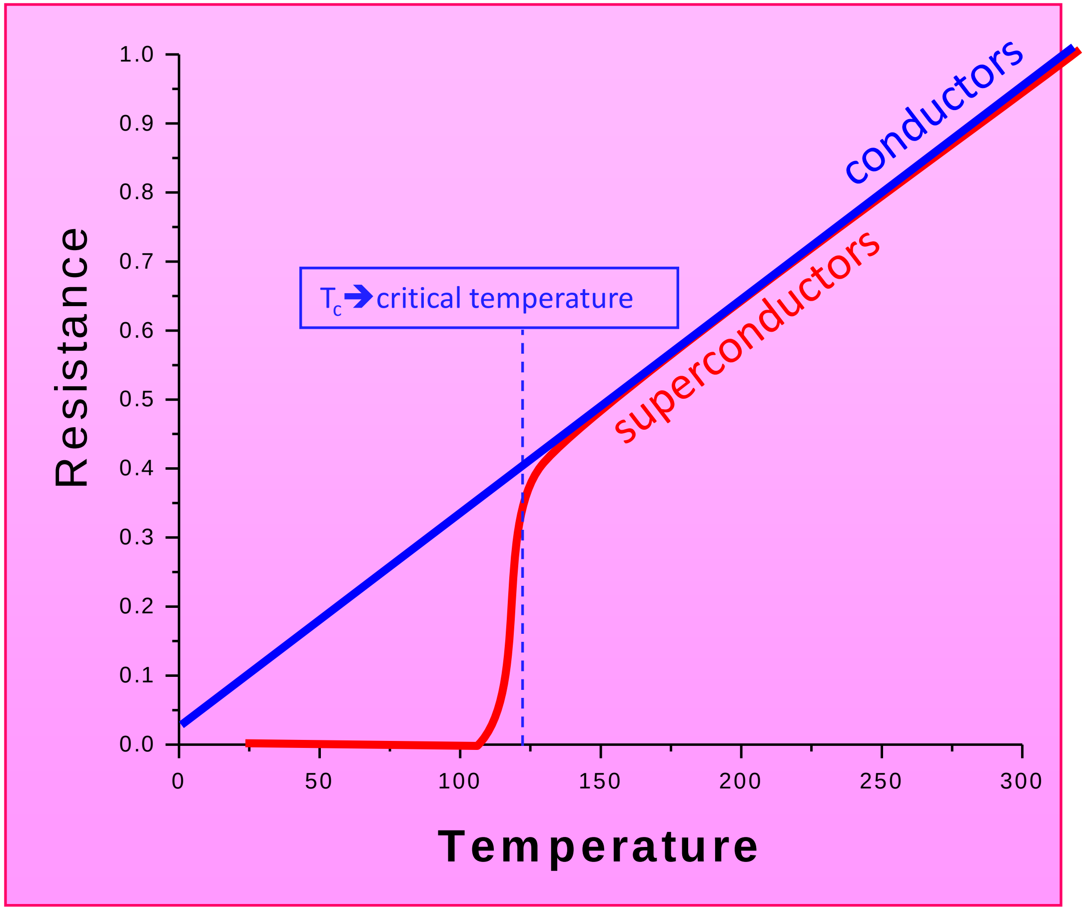
Heike Kamerlingh Onnes
(Nobel Prize 1913)

" A superconductor is a material that exhibits both **perfect conductivity and perfect diamagnetism**".

Basic Characteristics of SC

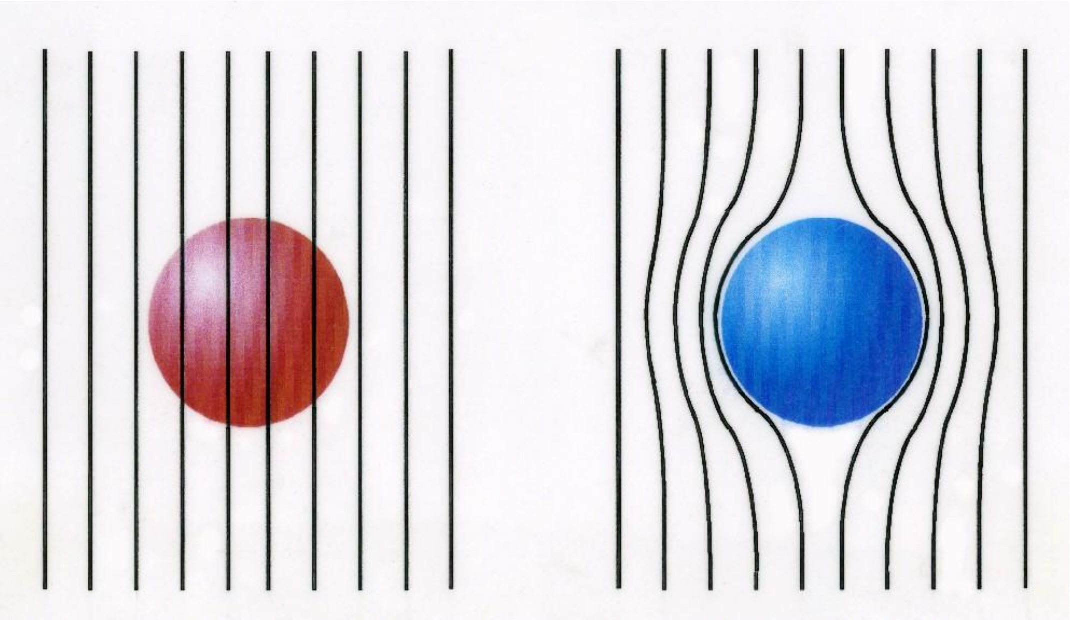
Perfect diamagnetism

Zero Resistance

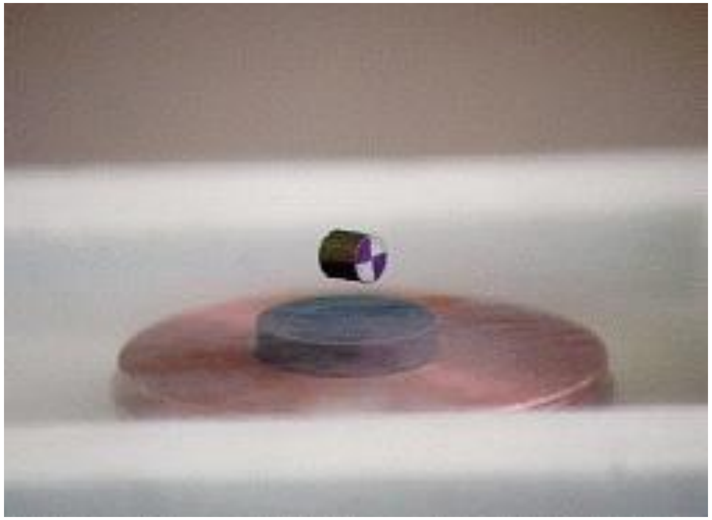


The Meissner (and Ochsenfeld) Effect

superconductors push out magnetic fields

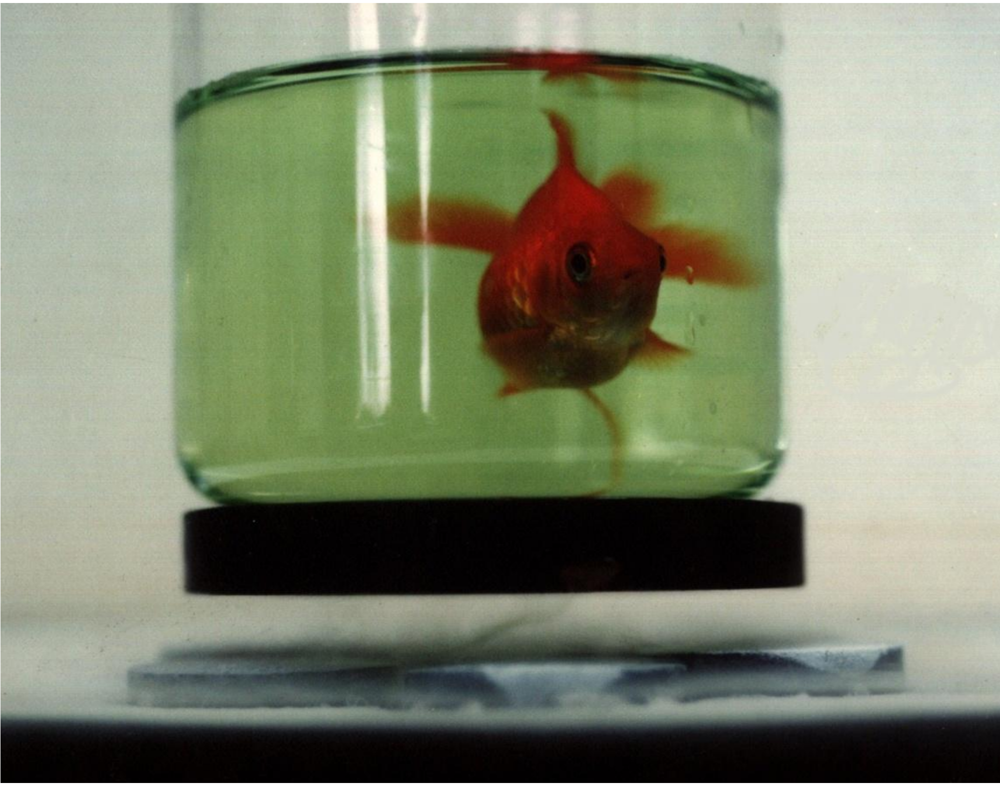


- and keep them out with constantly- flowing resistance-less currents



this ‘diamagnetic’ property is more fundamental than zero resistance

Levitation with High-Tc Superconductors



A kg or so of fish bowl

Superconductivity phenomena

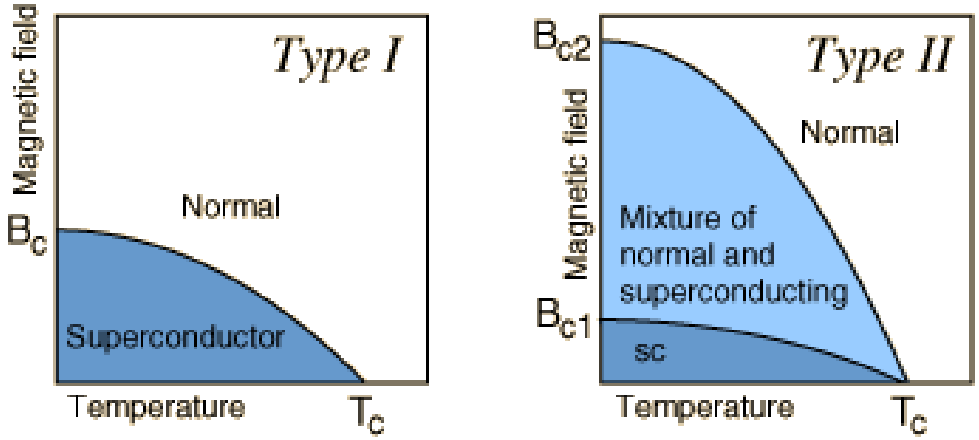
- Perfect conductivity $\sigma = \infty$
- Perfect diamagnetism $B = 0$
- Magnetic field suppresses superconductivity $H_c(T)$, $H_{c1}(T)$, $H_{c2}(T)$
- Magnetic flux is quantized in units of h/2e
- Dynamics of the lattice is important $T_c \propto M^{-\alpha}$
- Energy gap 2Δ
- T_c and energy gap are related
- Superconductivity mechanism in HTS is different from LTS

Magnetism:Properties of Superconductors

Superconductors can be classified into two types according to their interaction with an external magnetic field:

Type I

- Type I superconductors expel all magnetic flux
- Superconductivity ends when a critical flux is applied. Examples include mercury, lead, and tin.

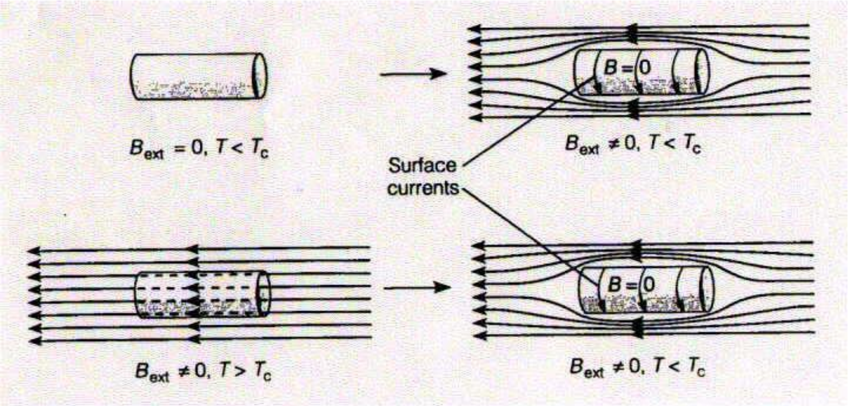


http://www.gitam.edu/eresource/Engg_Phys/semester_2/supercon/type_1_2.htm

Figure 7.1: Type I superconductors are different than Type II superconductors. This figure shows the comparison of graphs Bc vs Tc in both types. Type II has a mixed state while Type I does not.

Callister, W.D. 2012, 776-779.
Patel, M.J. et. al. Nat. Confer. Rec. Trend. Engr. Tech. 2011.

Type I - Meissner Effect

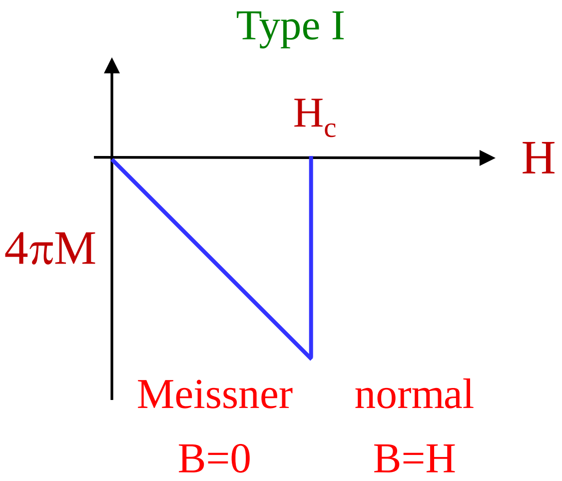


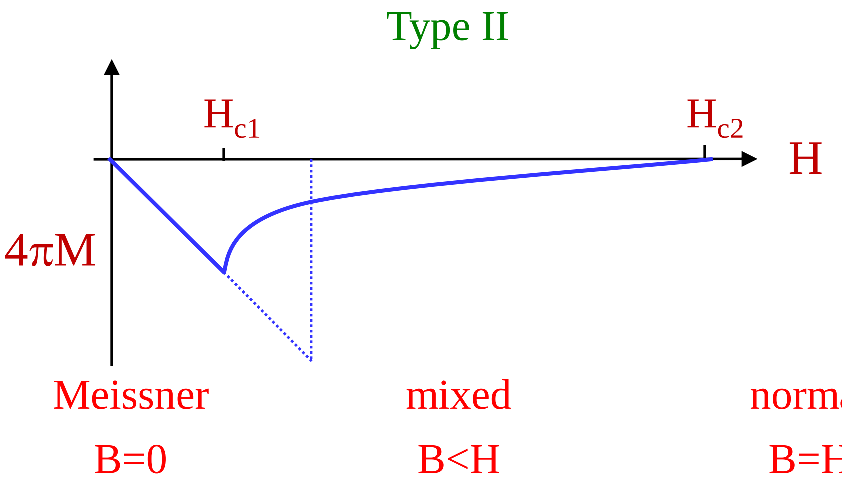
- Type I superconductors expel magnetic field. (Meissner Effect)

Type I Superconductors

Mat.	T_c (K)	Mat.	T_c (K)
Be	0	Gd*	1.1
Rh	0	Al	1.2
W	0.015	Pa	1.4
Ir	0.1	Th	1.4
Lu	0.1	Re	1.4
Hf	0.1	Tl	2.39
Ru	0.5	In	3.408
Os	0.7	Sn	3.722
Mo	0.92	Hg	4.153
Zr	0.546	Ta	4.47
Cd	0.56	V	5.38
U	0.2	La	6.00
Ti	0.39	Pb	7.193
Zn	0.85	Tc	7.77
Ga	1.083	Nb	9.46

Magnetization of superconductors





Magnetic field suppresses superconductivity

Type II Superconductors

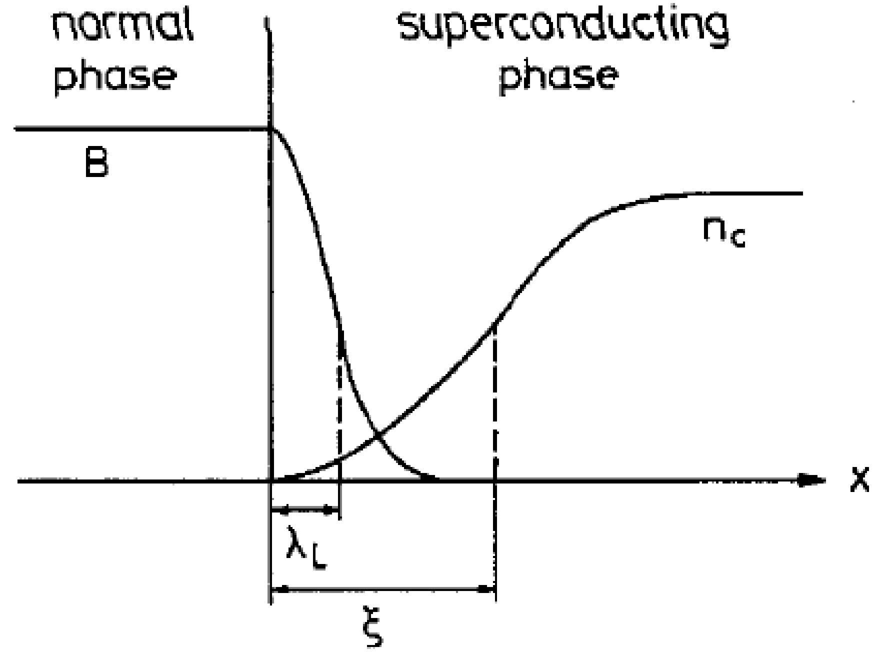
Material	Transition Temp (K)	Critical Field (T)
NbTi	10	15
PbMoS	14.4	6.0
V_3Ga	14.8	2.1
NbN	15.7	1.5
V_3Si	16.9	2.35
Nb_3Sn	18.0	24.5
Nb_3Al	18.7	32.4
$Nb_3(AlGe)$	20.7	44
Nb_3Ge	23.2	38

From Blatt, Modern Physics

Physics of type I and II superconductors

u "London Penetration Depth" l_L

is the e-fold decay length of the magnetic field from the superconductor skin due to the Meissner effect (in the range of 10 to 10^3 nm)



u "Coherence Length" x

the average size of Cooper in the superconductor (in the range of 10 to 100 nm, I.e. much larger than the inter-atomic distance typically of 0.1 to 0.3 nm.

Ginzburg-Landau Parameter k

$$\kappa = \lambda_L / \xi \Rightarrow \begin{cases} k < 1/\sqrt{2} \Leftrightarrow \text{type I} \\ k > 1/\sqrt{2} \Leftrightarrow \text{type II} \end{cases}$$

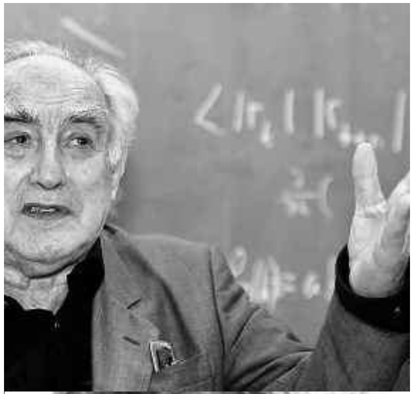
material	In	Pb	Sn	Nb
λ_L [nm]	24	32	≈ 30	32
ξ [nm]	360	510	≈ 170	39

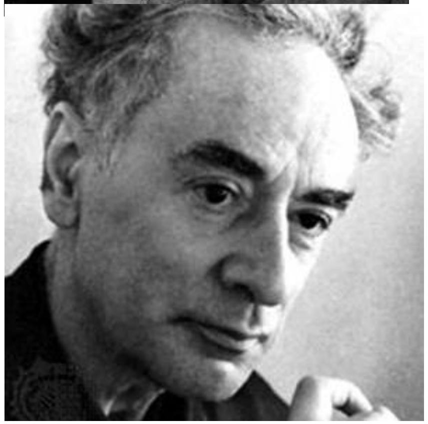
There are two main theories in SC

First Theory

After discovery of superconductivity, initially many phenomenological theories have been developed:

- London theory (1930s)
- Macroscopic quantum model of superconductivity
- Ginzburg-Landau-Abrikosov-Gorkov theory (early 1950s)
- Ginzburg-Landau Theory – describes the properties of superconductors in magnetic fields





Second Theory

- Microscopic BCS theory – describes why materials are superconducting

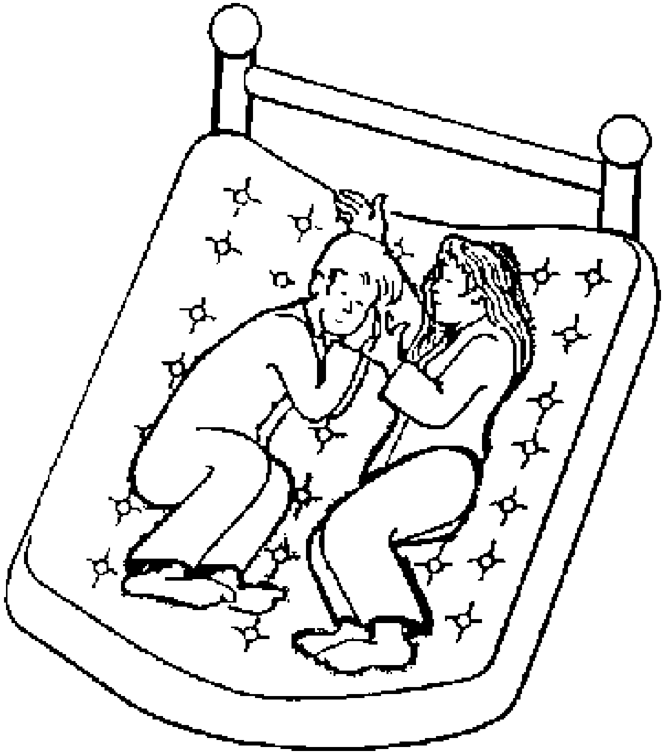
The BCS attractive mechanism

is due to electrons slightly deforming the crystal lattice

A theoretician would describe this attraction as due to exchange of

'virtual phonons'

- but we can visualise it as the "sagging mattress effect"!



A sagging mattress draws two sleepers together.

Randy Simon, Andy Smith, Superconductors

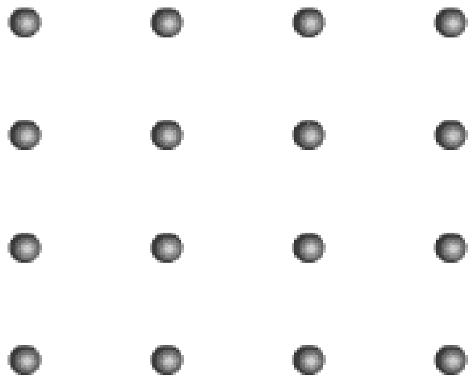
Cooper Pair

- Two electrons that appear to "team up" in accordance with theory - BCS or other - despite the fact that they both have a negative charge and normally repel each other.

- Below the superconducting transition temperature, paired electrons form a condensate - a macroscopically occupied single quantum state - which flows without resistance

- Electrons - Fermions

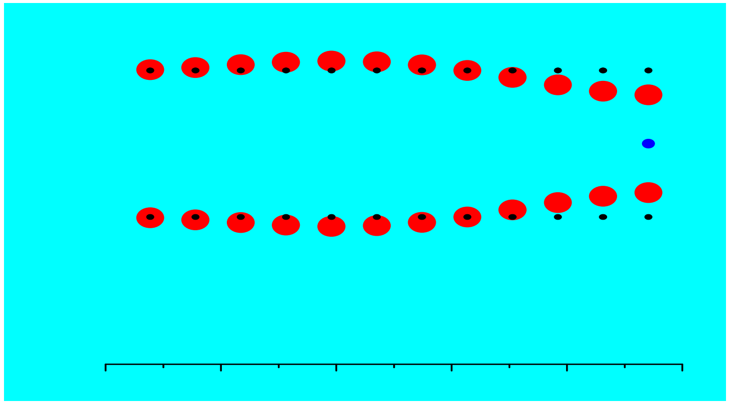
- Cooper pair - Bosons



Classical model of superconductivity

1957 John Bardeen, Leon Cooper, and John Robert Schrieffer

An electron on the way through the lattice interacts with lattice sites (cations). The electron produces phonon.



The lattice deformation creates a region of relative positive charge which can attract another electron.

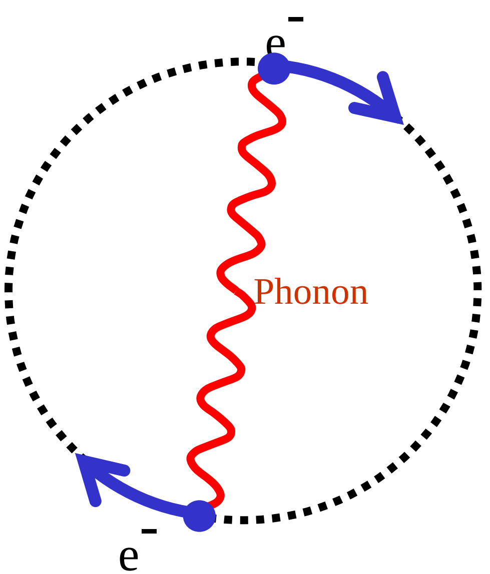
During one phonon oscillation an electron can cover a distance of ~10^4Å. The second electron will be attracted without experiencing the repulsing electrostatic force .

Cooper Pair

Creation of a C-Pairs diminishes energy of electrons. Breaking a pair (e.g. through interaction with impurity site) means increase of the energy.

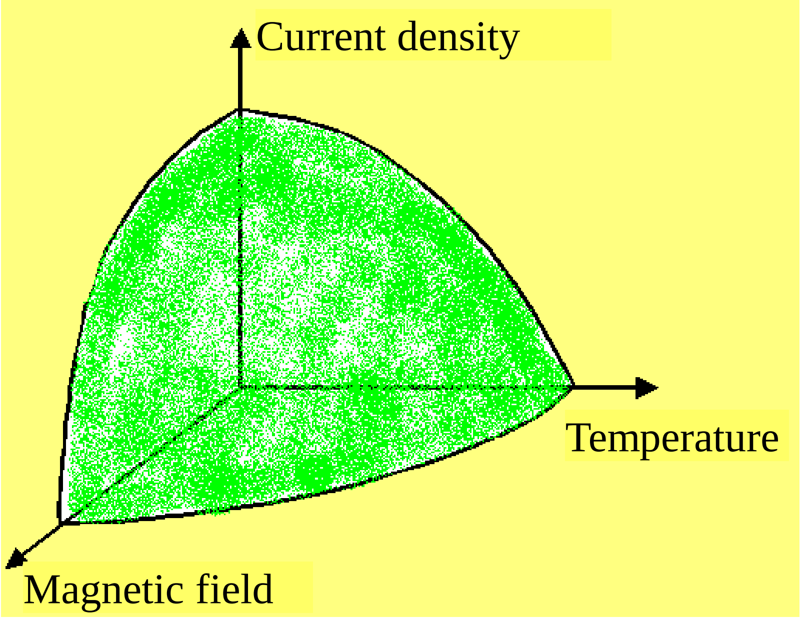
A movement of the C-P when a supercurrent is flowing, is considered as a movement of a centre of the mass of two electrons creating C-P.

All the C-P are in the same quantum state with the same energy. A scattering by a lattice imperfection (impurity) can not change quantum state of all C-P at the same time (collektive behaviour).



What destroys superconductivity?

A current: produces magnetic field which in turn destroys superconductivity.

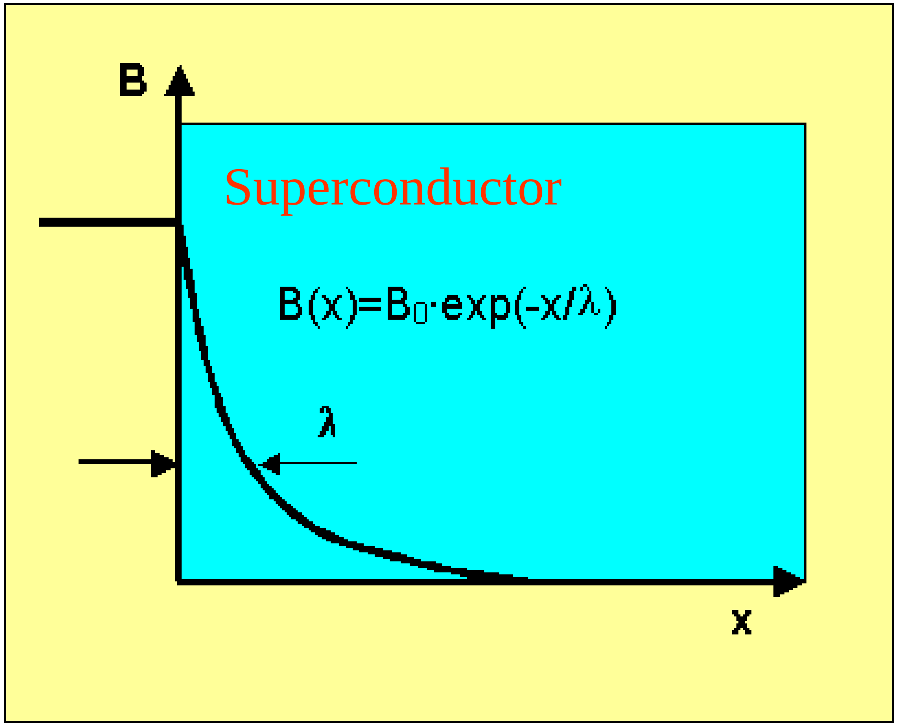


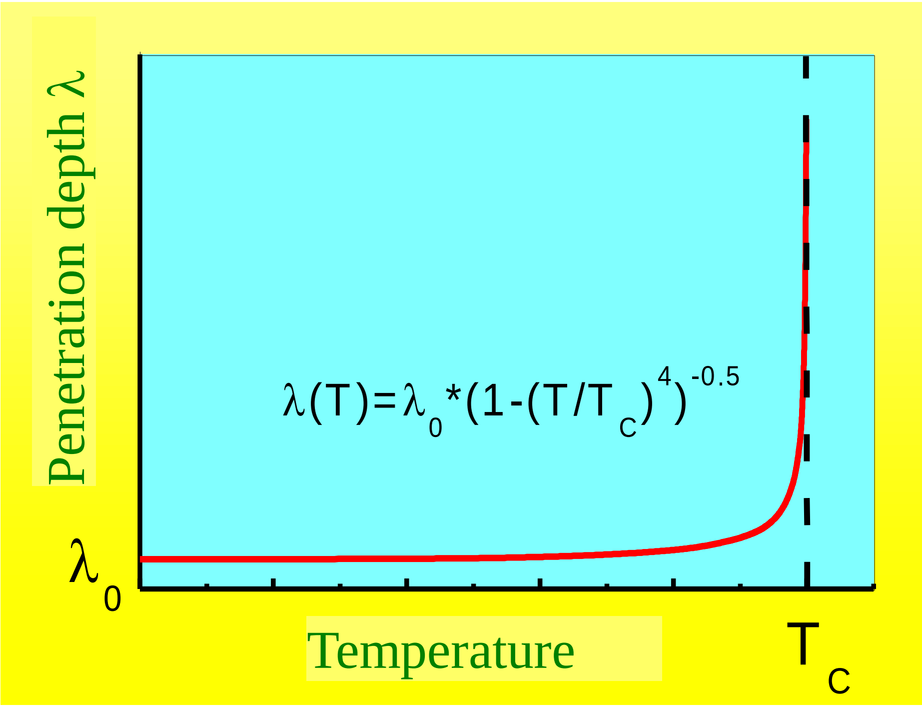
High temperatures: strong thermal vibration of the lattice predominate over the electron-phonon coupling.

Magnetic field: the spins of the C-P will be directed parallel.

should be antiparallel in C-P)

Penetration depth

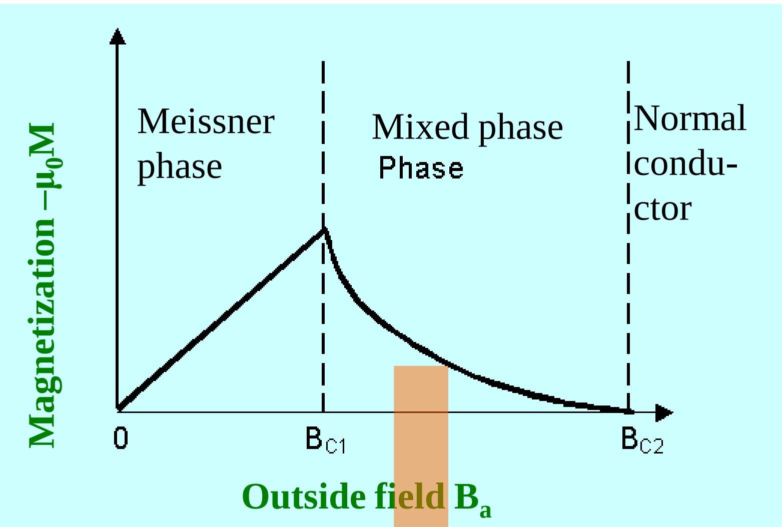


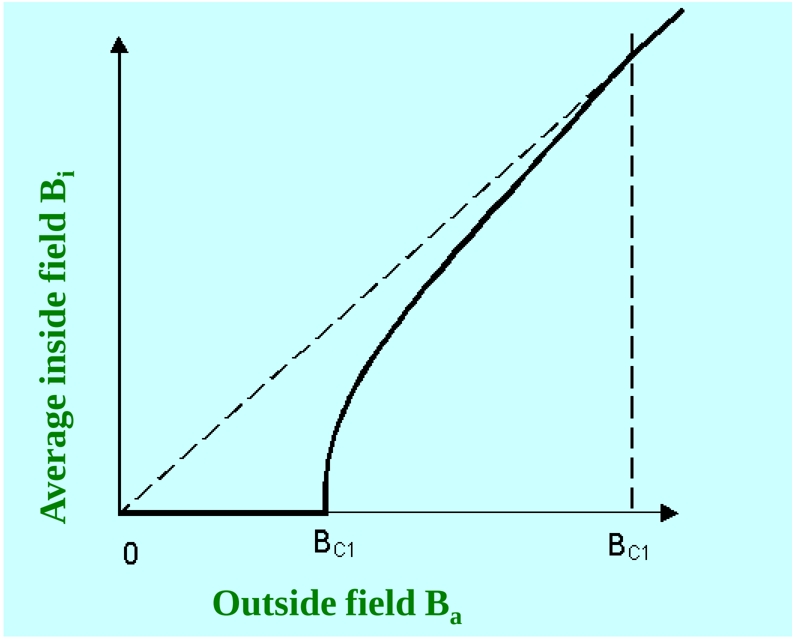


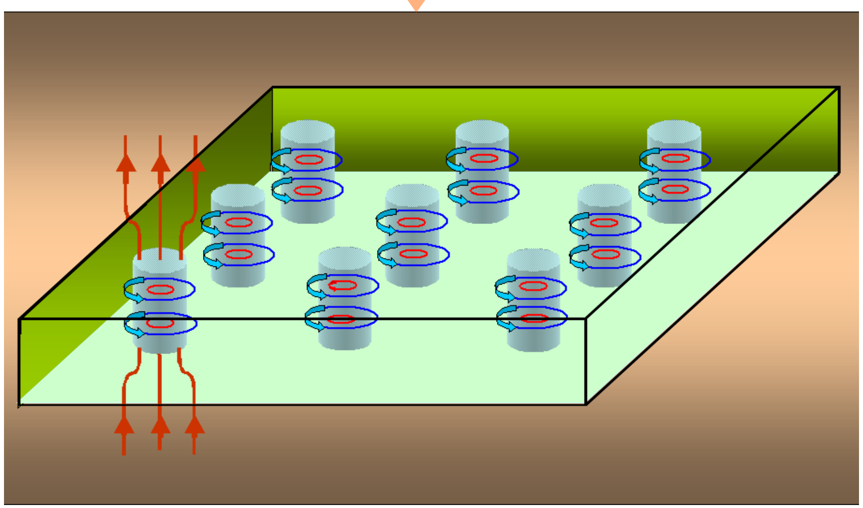
λ depicts the distance where B(x) is e-time smaller than on the surface

SC type II in a magnetic field

$B_i = B_a + \mu_0 M$

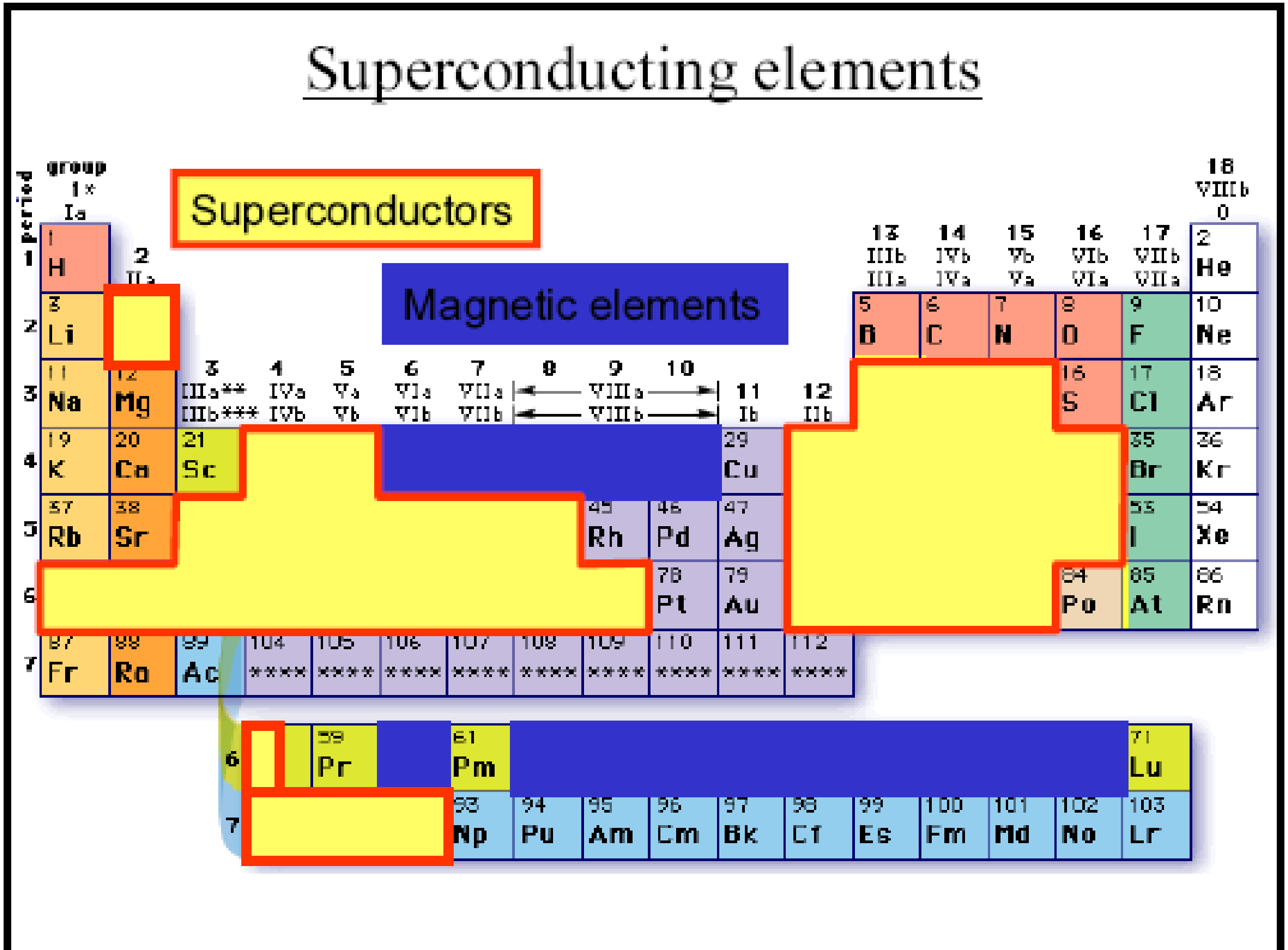






Vortex-lattice in superconductor type II. Magnetic flux of a vortex is quantized:
$\Phi_0 = h/2e \cong 2.07 \cdot 10^{-15} \mathrm{Tm}^2$

A big class of new materials
(> 2000 compounds)

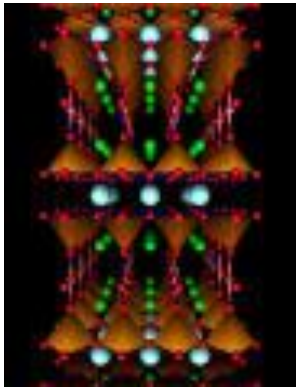


Break through High Tc SC

In 1986 HTCS ($La_{1.85}Ba_{0.15}CuO_4$, T_c=30K) have been discovered. The higher critical temperature for HTCS is 138 K ($Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$)

High Temperature Superconductors (1986)

Received the Nobel Prize 1987 for discovery of the first of the copper-oxide superconductors

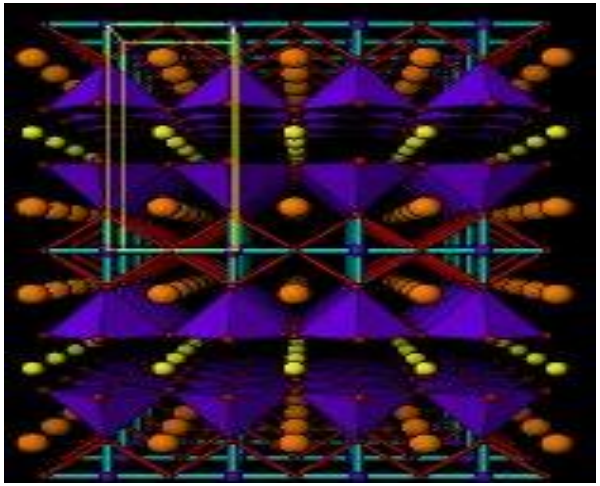


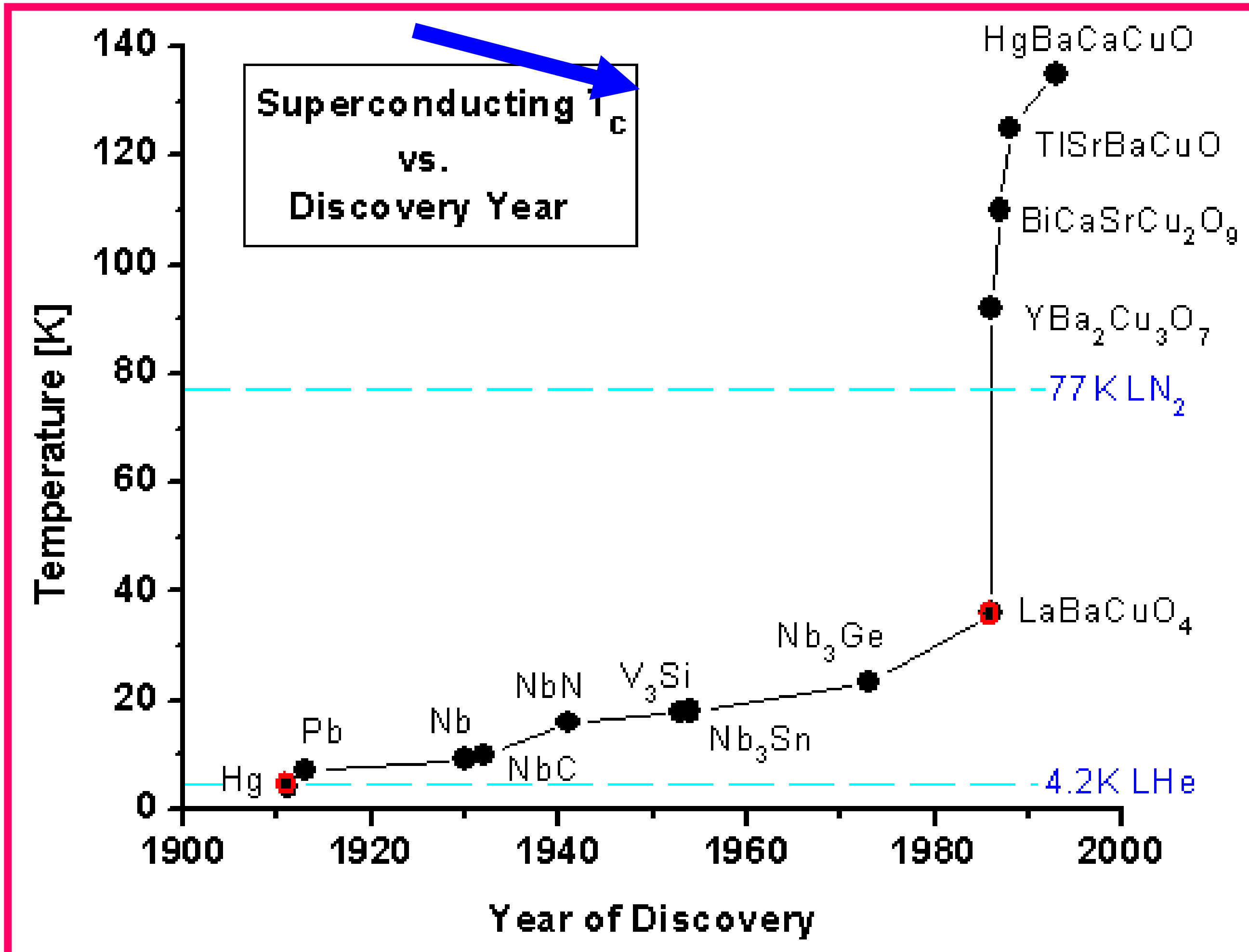
gh-T_c Superconductivity

Paul Chu

164 K

Alex Müller and Georg Bednorz

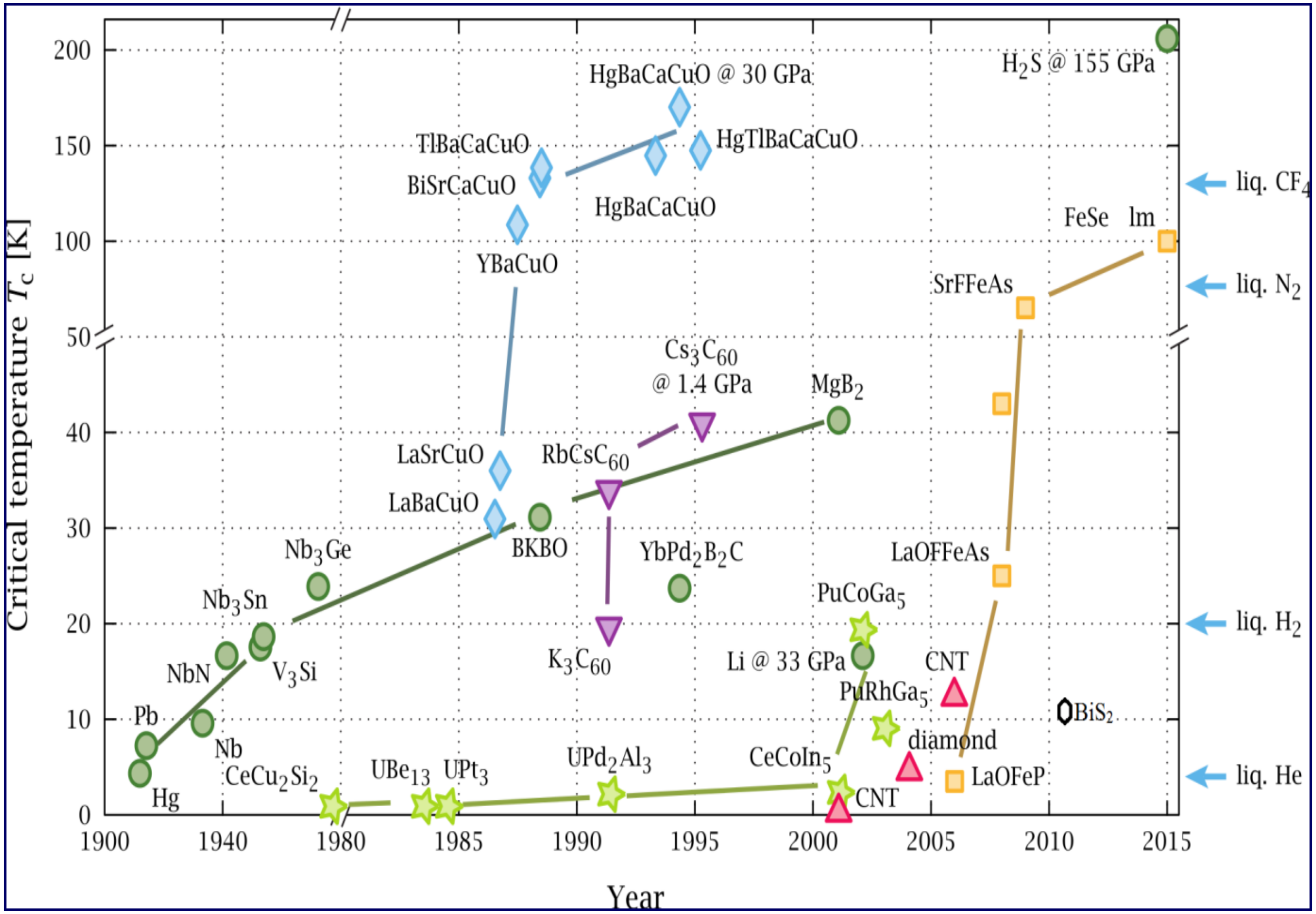




Development of Superconducting Materials

Kamerlingh Onnes to M.I. Eremets

Superconductivity (1911 to 2015 (104 years))



T_c from 1911 to till date

~ 4 K

~ 203 K

The dream - “Tomorrow’s Superconducting World”

Energy Saving:
power lines
electric motors
transformers

magnetically launched space shuttle

Medical Diagnostics:
Magnetic Resonance Imaging
SQUID:
Brain activity
Heart function

Cargo-carrying submarines, all-electric US Navy

350 mph levitated Intercity trains

Computing:
1000 times faster supercomputers

Information Technology:
much faster, wider band communications

Underground rapid transit:
Heathrow to Gatwick in 10 minutes

Applications- Transport

- **Maglev trains (Paris to Rome in just over 2 hours!)**
- **Frictionless bearings increasing efficiency of electrical motors and generators in electric-powered transport**
- **Smaller, lighter gyros in spacecraft and satellites**

Maglev trains

Maglev- Magnetic levitation trains which float over a guideway replacing steel wheels and tracks.
Frictionless so can travel up to 500km/h (310mph) – viable option replacing aircraft for some journeys.

China- Shanghai transrapid shuttles 19 miles from Pudong airport to Longyang train station in 8 min flat at 430 km/h

Japan's maglev train

MAGNETIC LEVITATION TRAINS

- **Commercial Track**
- **Length – 30.5 km**
- **Top speed – 501km/h**
- **Service speed – 430km/h**
- **6 million passengers so far**

Shanghai, China

ACKNOWLEDGEMENTS

DST

UGC

CSIR

AICTE

BRNS

CSIR

TWAS

INDO-FRENCH

Organizer

Thank you