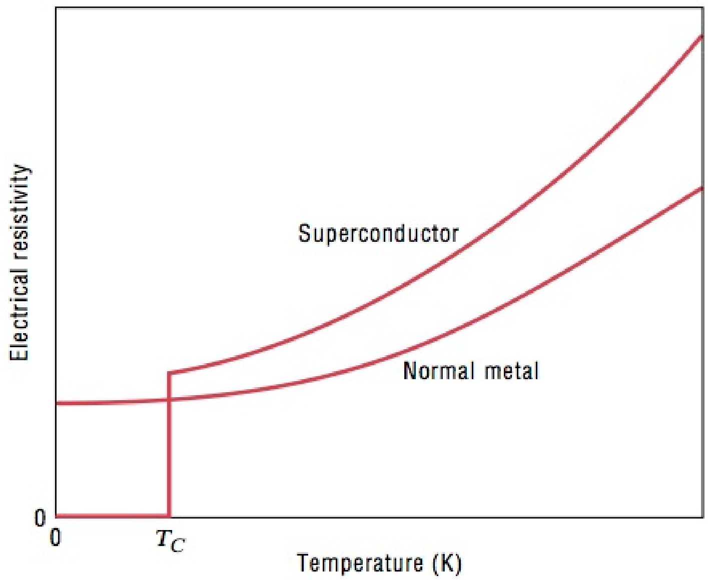
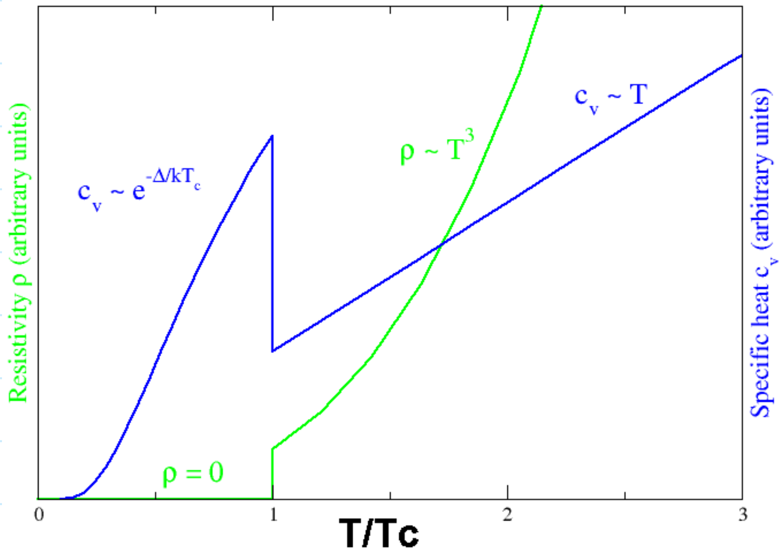
Unit 10 - Superconductors

1. What is superconductivity



2^{nd} order phase transition with $\Delta T \lesssim 0.001\,K$
and $\rho < 10^{-25}\,\Omega \cdot m$

no latent heat but change in heat capacity and conductivity ...



2. History.

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

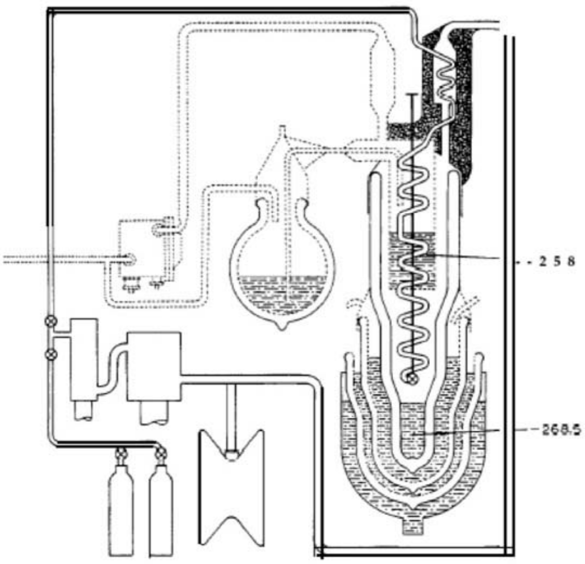
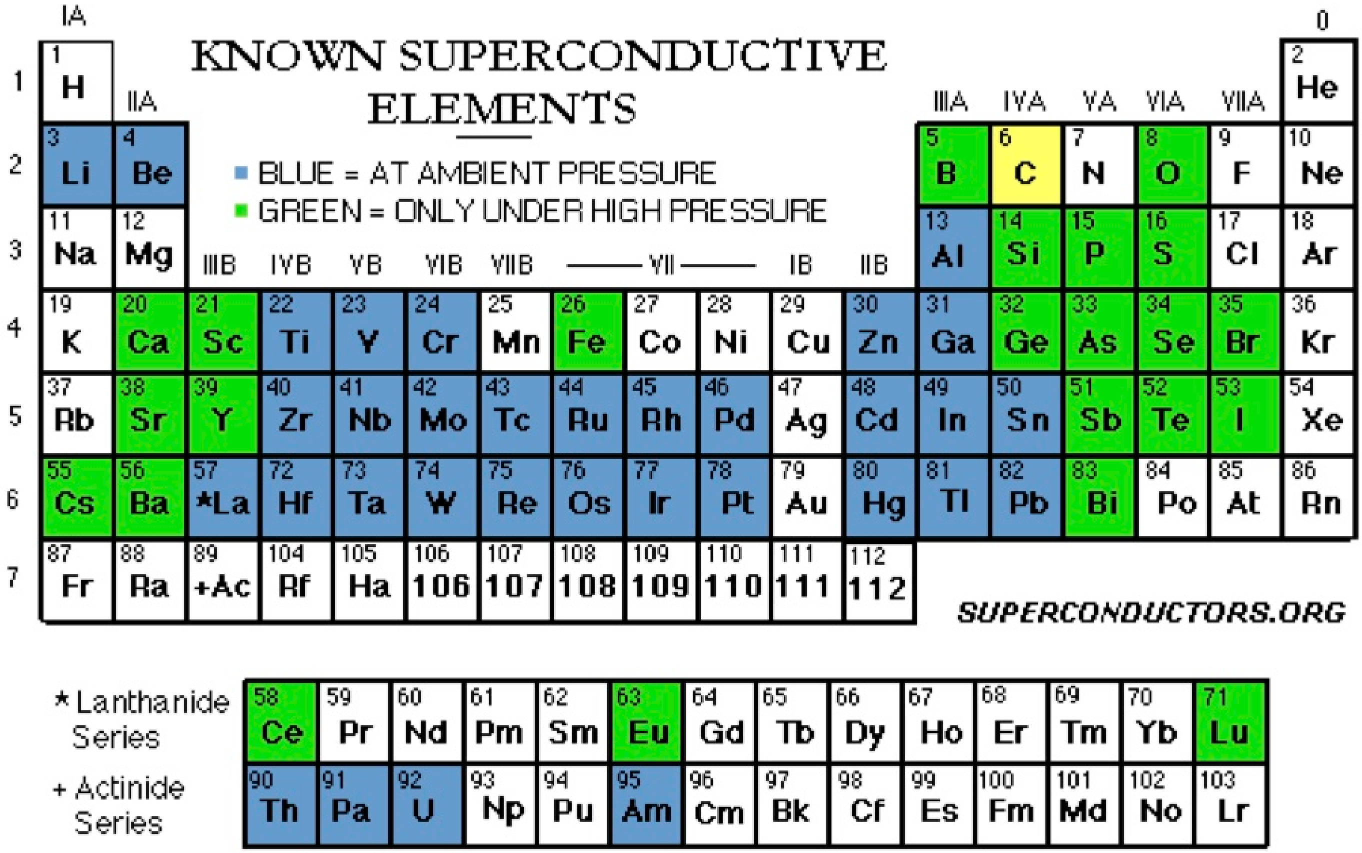


Fig. 7.

Lead (Pb)	7.196 K	FCC
Lanthanum (La)	4.88 K	HEX
Tantalum (Ta)	4.47 K	BCC
Mercury (Hg)	4.15 K	RHL
Tin (Sn)	3.72 K	TET
Indium (In)	3.41 K	TET
Palladium (Pd)*	3.3 K	(see note 1)
Chromium (Cr)*	3 K	(see note 1)
Thallium (Tl)	2.38 K	HEX
Rhenium (Re)	1.697 K	HEX
Protactinium (Pa)	1.40 K	TET
Thorium (Th)	1.38 K	FCC
Aluminum (Al)	1.175 K	FCC
Gallium (Ga)	1.083 K	ORC
Molybdenum (Mo)	0.915 K	BCC
Zinc (Zn)	0.85 K	HEX
Osmium (Os)	0.66 K	HEX
Zirconium (Zr)	0.61 K	HEX
Americium (Am)	0.60 K	HEX
Cadmium (Cd)	0.517 K	HEX
Ruthenium (Ru)	0.49 K	HEX
Titanium (Ti)	0.40 K	HEX
Uranium (U)	0.20 K	ORC
Hafnium (Hf)	0.128 K	HEX
Iridium (Ir)	0.1125 K	FCC
Beryllium (Be)	0.023 K (SRM 768)	HEX
Tungsten (W)	0.0154 K	BCC
Platinum (Pt)*	0.0019 K	(see note 1)
Lithium (Li)	0.0004 K	BCC
Rhodium (Rh)	0.000325 K	FCC


KNOWN SUPERCONDUCTIVE ELEMENTS
BLUE = AT AMBIENT PRESSURE
GREEN = ONLY UNDER HIGH PRESSURE
SUPERCONDUCTORS.ORG
* Lanthanide Series
+ Actinide Series

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 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.	General Electric	University of

138 Physics 1973

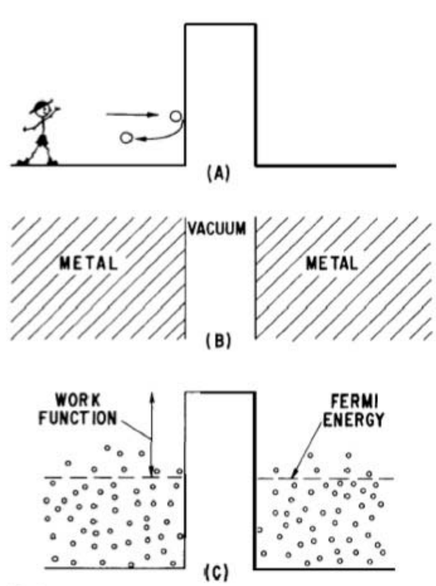
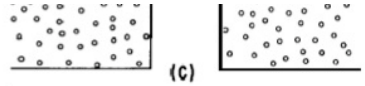


Fig. 1.

		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

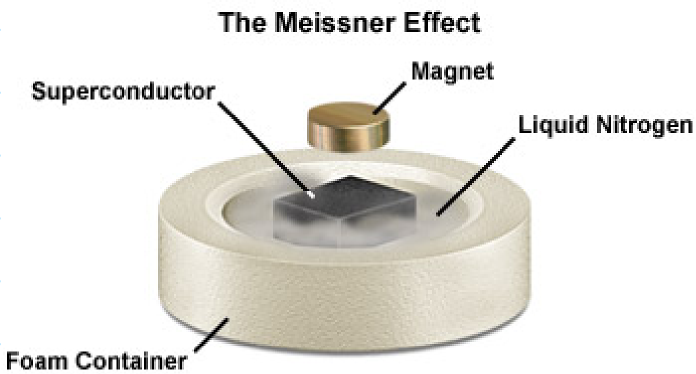
•http://www.nobel.se/physics/laureates

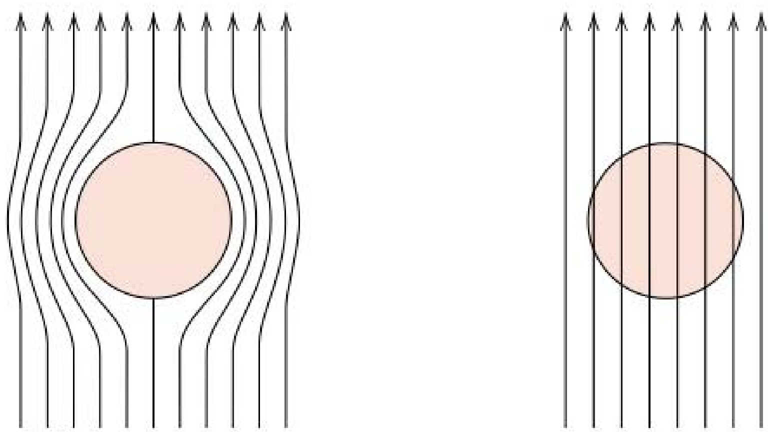


(c)

Fig. 1.

3. Meissner effect

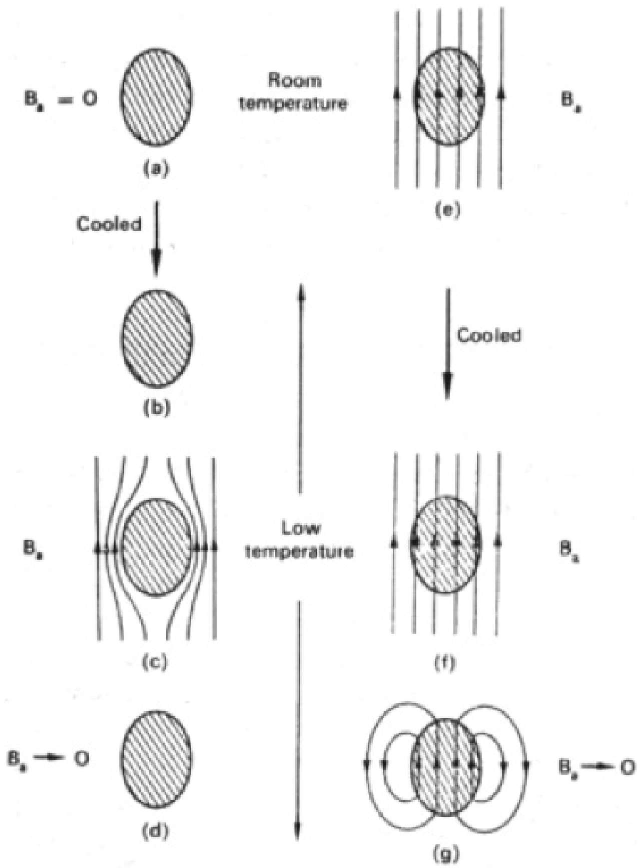




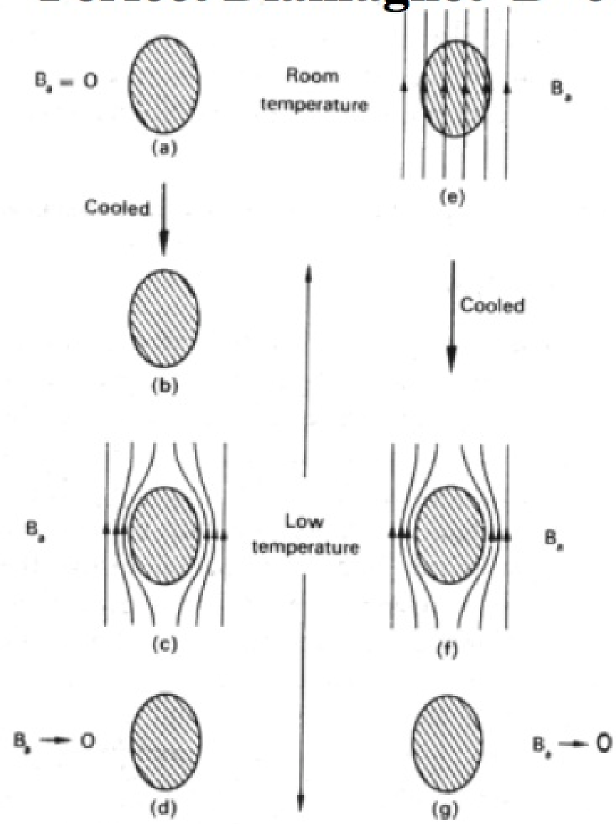
(a) (b)

FIGURE 18.23 Representation of the Meissner effect. (*a*) While in the superconducting state, a body of material (circle) excludes a magnetic field (arrows) from its interior. (*b*) The magnetic field penetrates the same body of material once it becomes normally conductive.

Perfect Conductor R=0



Perfect Diamagnet B=0



Meissener Effect

https://www.youtube.com/watch?v=r8388RRl2h4

https://www.youtube.com/watch?v=lC-3li6ScUE

https://www.youtube.com/watch?v=xPyIDFEmMlE

4. Effect of magnetic fields & currents

$$H_C(T) = H_C(0)\left(1 - \frac{T^2}{T_C^2}\right)$$

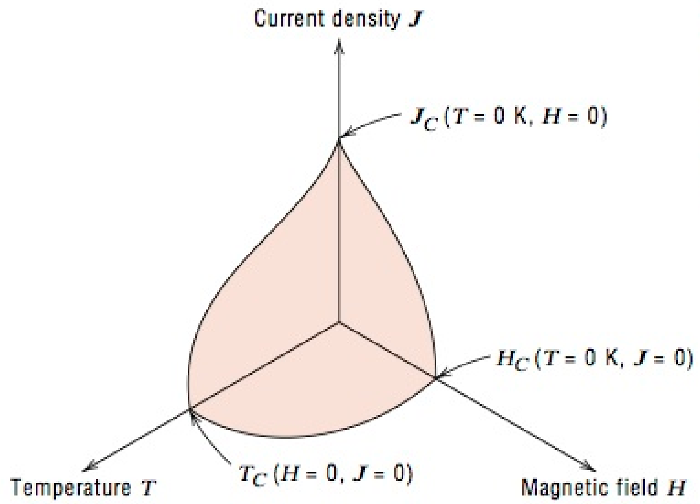
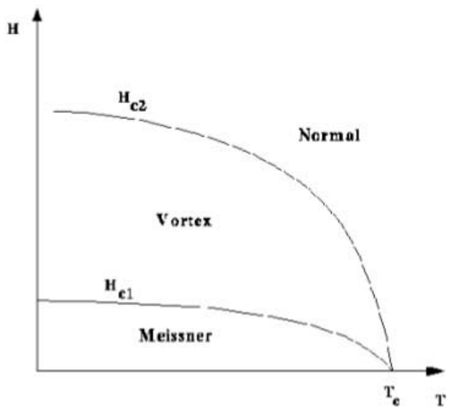
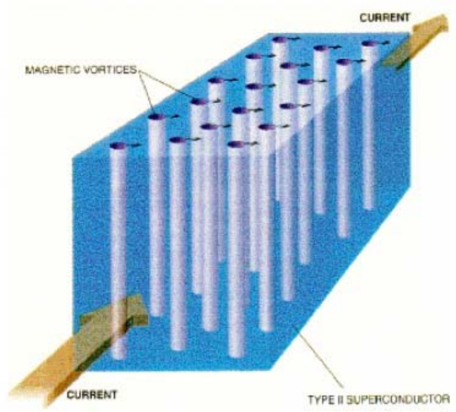


FIGURE 18.22 Critical temperature, current density, and magnetic field boundary separating superconducting and normal conducting states (schematic).

5. Type II 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

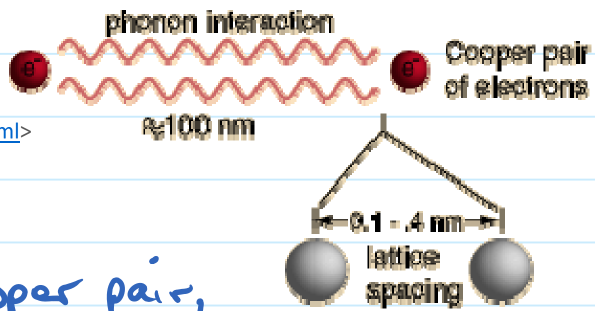
Table 18.7 Critical Temperatures and Magnetic Fluxes for Selected Superconducting Materials

Material	*Critical Temperature* T_C *(K)*	*Critical Magnetic Flux Density* B_C *(tesla)*[a]
	Elements[b]	
Tungsten	0.02	0.0001
Titanium	0.40	0.0056
Aluminum	1.18	0.0105
Tin	3.72	0.0305
Mercury (α)	4.15	0.0411
Lead	7.19	0.0803
	Compounds and Alloys[b]	
Nb-Ti alloy	10.2	12
Nb-Zr alloy	10.8	11
$PbMo_6S_8$	14.0	45
V_3Ga	16.5	22
Nb_3Sn	18.3	22
Nb_3Al	18.9	32
Nb_3Ge	23.0	30
	Ceramic Compounds	
$YBa_2Cu_3O_7$	92	—
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	—
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	—
$HgBa_2Ca_2Cu_2O_8$	153	—

6. BCS theory

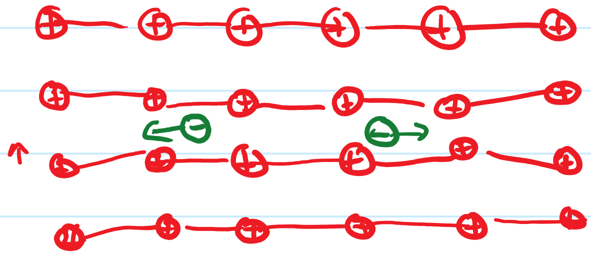
Condensation of Cooper pairs.

Cooper Pairs



From <http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/coop.html>

Fig. 9.12 Formation of a Cooper pair



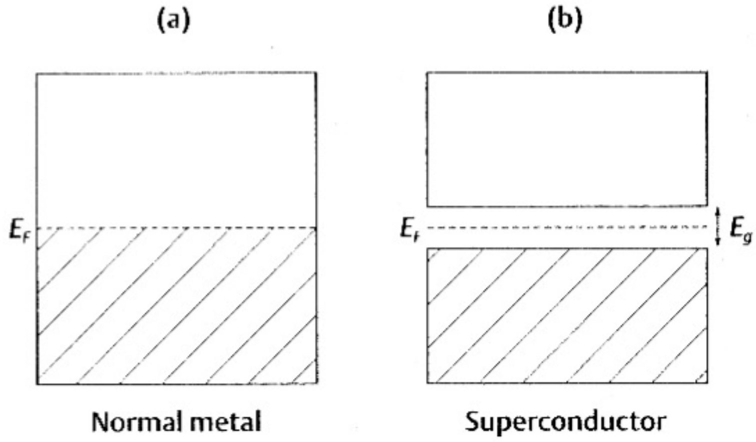


Figure 9.13 Occupation of energy levels at absolute zero in (a) a normal metal and (b) a superconductor. E_F denotes the Fermi energy. Note that in the superconductor there is a gap between the highest filled states and the lowest vacant states.

$$E = 3.52 k_B T_c \sqrt{1 - (T/T_c)}$$

High temperature superconductivity.

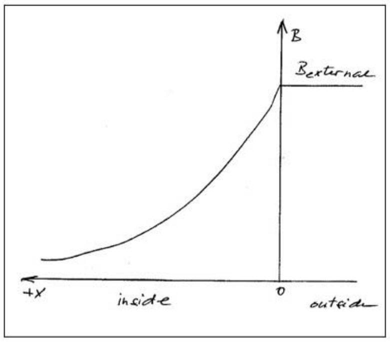
1. BCS experimental evidence.

surface current.

Penetration of magnetic field below the surface of superconductors
The surface current is distributed in the surface layer, the layer carrying the electric current has a finite thickness, and because of this, the external magnetic field partially penetrates into the interior of the superconductor,

$$B(x) = B_{external} \exp\left(-\frac{x}{\lambda}\right)$$

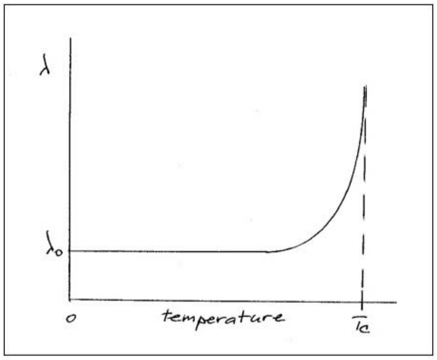
λ = penetration distance at temperature T;



Temperature dependence of penetration distance
λ = penetration distance at temperature T;
λ_0 = penetration distance at temperature T=0.

$$\lambda = \frac{\lambda_0}{\sqrt{1-\left(\frac{T}{T_c}\right)^4}}$$

λ_0 = 30 - 130 nm, depending on the superconductor material



isotope effect (exchange phonons) $f \propto \frac{1}{\sqrt{M}}$ $T_c \propto \frac{1}{\sqrt{M}}$

Magnetic flux quantization

$\omega = \sqrt{\frac{k}{m}}$ ⇐ Simple harmonic motion.

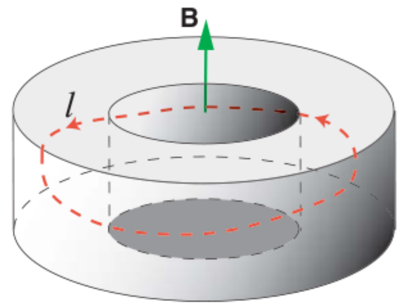
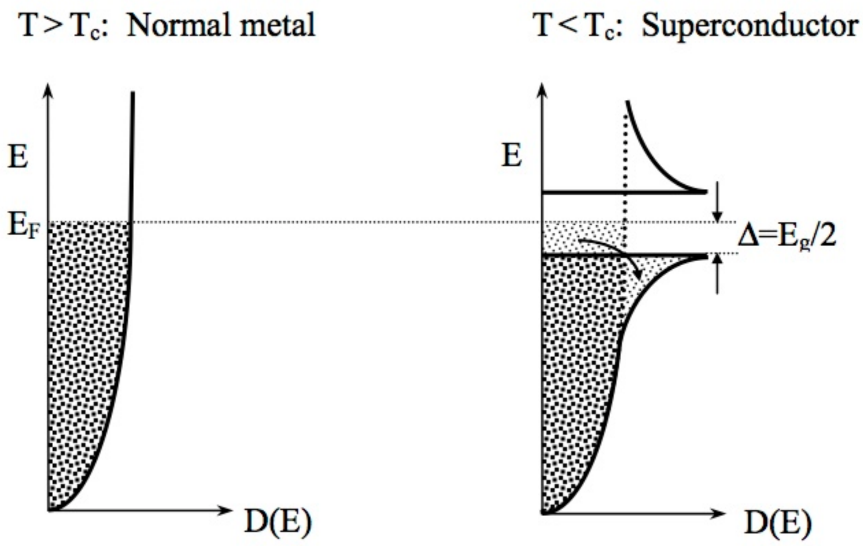


Figure 1.3: Magnetic flux through the hole in a superconductor is quantized.

Energy gap.



Measuring the gap E_g

1. **Infrared Absorption**: The **absorption** coefficient is measured versus the energy of infrared or microwave photons, analogous to a gap measurement in a semiconductor. (Only the energy scale is meV insetad of eV). In the superconducting state, photons cannot be absorbed when their energy is less than $\mathbf{E_g}$. (Lect. 30, Slide 4)
2. **Tunneling**: Electrons tunnel from a metal through an insulator into a superconductor. Current-versus-voltage **I(V)** curves are measured. The current vanishes for $|V|<\Delta/e$. The derivative **dI/dV** is related to the density of states **D(E)**. (Lect. 30, Slide 5)
3. **Photoemission**: The number of emitted photoelectrons versus their final state energy E_{fin} replicates the density of states **D(E)** . A superconductor does not have any states in the energy region $E_F-\Delta < E < E_F$. Photoemission can measure the **k-dependence of E_g** and thereby determine the orbital angular momentum ***l* of the pairs**. That is particularly important for high temperature superconductors, which are d-wave (Lect. 30, Slide 6).

2. High T_c

Type 2 Superconductors

From <http://www.superconductors.org/Type2.htm>

Structure

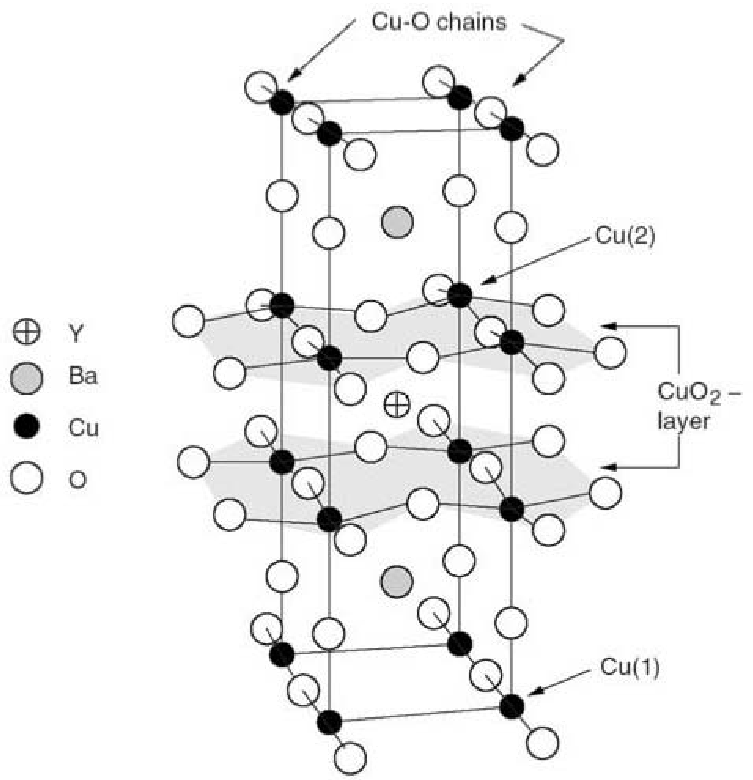
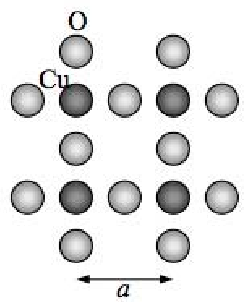


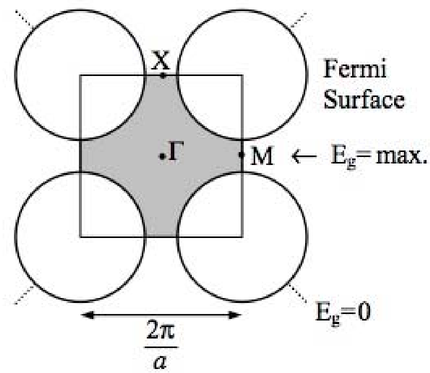
Figure 9. Crystal lattice structure of the High – T_c superconductor, $YBa_2Cu_3O_7$.

Superconductivity occurs in $Cu^{2+}O^{2-}$ **planes** embedded into an ionic lattice.

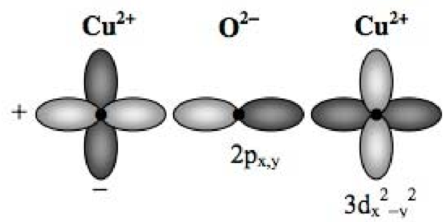
Real space ($\mathbf{x},\mathbf{y}$)



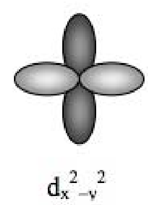
Reciprocal space ($\mathbf{k_x}, \mathbf{k_y}$)



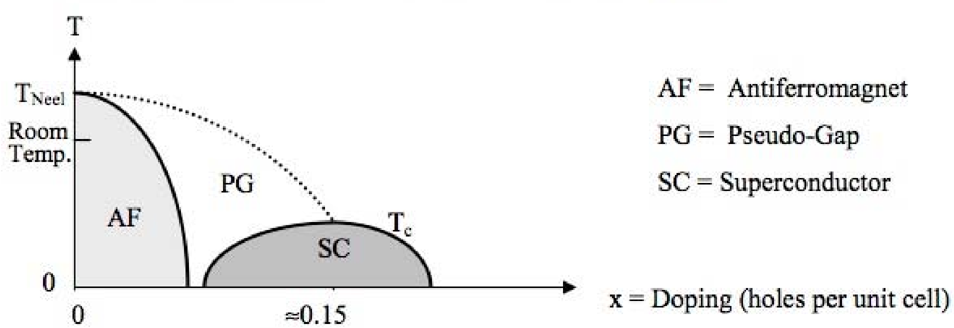
ψ of single electrons



Ψ of pairs (d-wave)



The superconducting carriers are **holes** introduced by **doping**.



The big open question is the nature of the boson that gives rise to pairing according to the diagram on p. 1 (magnon?, phonon?, complex mixture of those?).

Fin