Introduction to superconductivity

Textbook: “Introduction to superconductivity”
by A.C.Rose-Innes & E. H. Rhoderick 2nd Ed.

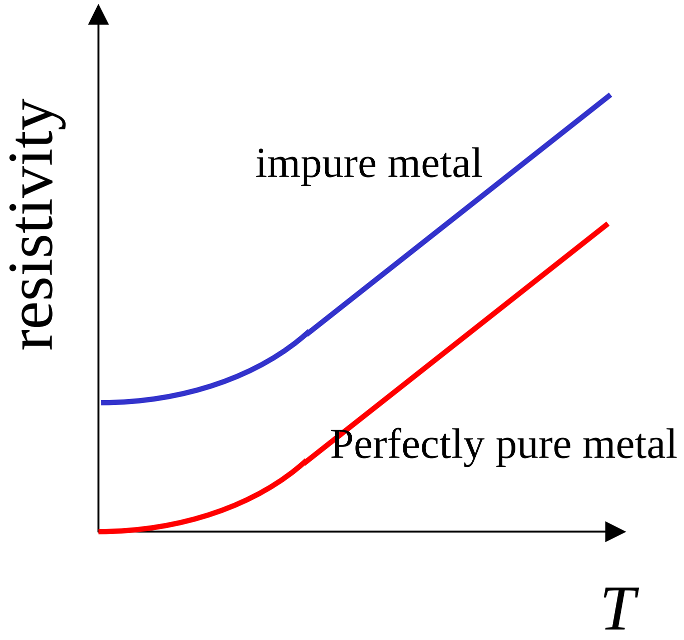
References:
“Introduction to superconductivity”
by M. Tinkham 2nd Ed.
“superconductivity” by C. P. Poole, Jr., H. A. Farach, and R. J. Creswick

Outline

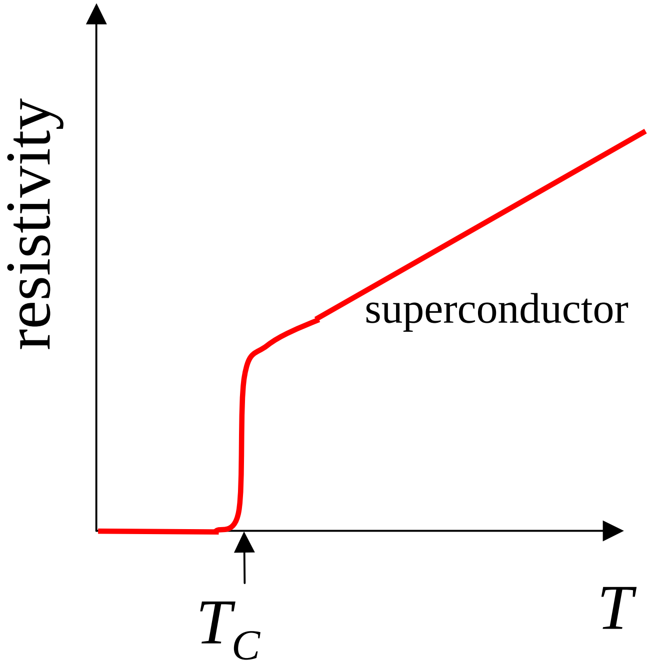
1 Introduction-zero resistance
2. Perfect diamagnetism
3. Electrodynamics/The London theory
4. The critical magnetic field
5. Thermodynamics of the transition
6. The intermediate state
7. Transport currents in superconductors
8. The superconducting properties of small specimens
9. Ginzburg- Landau theory
9. The microscopic theory/BCS theory
10. Tunneling/Josephson effect
11. Type-II superconductivity
12. Hi-Tc superconductors

1. Introduction- Zero resistance

Zero resistance



Residual resistivity ρ_0



Critical temperature

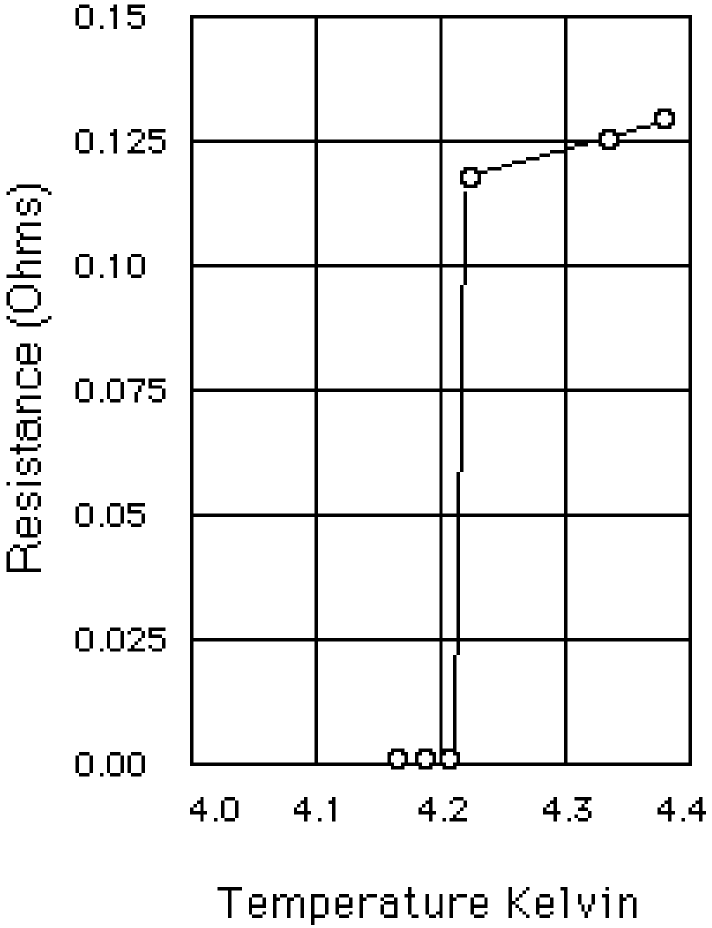
transition temperature

Discovery of superconductivity

H. Kamerlingh Onnes
(Leiden University)

He was the first to liquify helium (1908), for which he was awarded the Nobel prize in 1913, and he discovered superconductivity in 1911

According to Onnes, "Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state".



H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

100 years in superconductivity

Discovery of superconductivity H. Kamerlingh Onnes(1911) in Hg
1913 Nobel prize

Perfect diamagnetism: Meissner and Ochsenfeld(1933)

London equation: F. and H. London(1933)

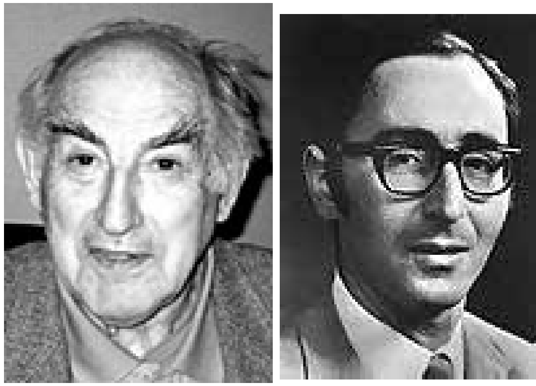
Ginzburg-Landau theory: 1950s
2003 Nobel prize (with Abrikosov)

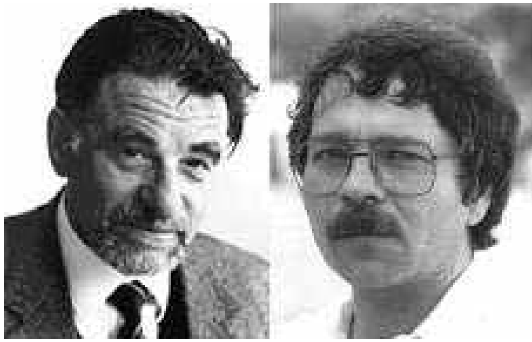
Isotope effect: H. Frohlich(1950)

BCS theory: J. Bardeen, L. Cooper and J.R. Schrieffer(1957) 1972 Nobel prize

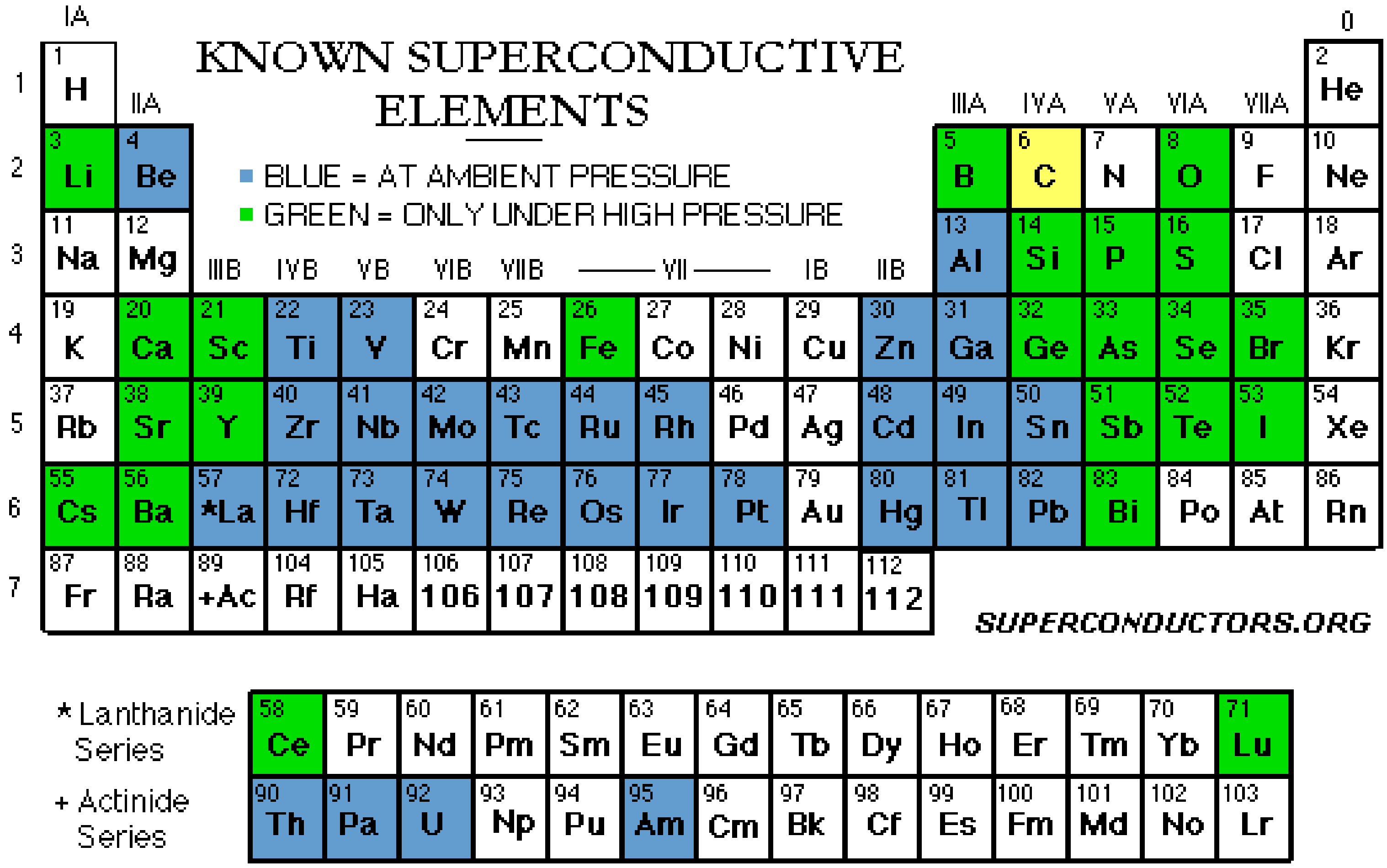
Tunneling: Josephson (1957) 1973 Nobel prize

Hi-Tc superconductivity: J. G. Bednorz and K. A. Muller(1986) in Ba-La-Cu-O system. 1987 Nobel prize





Known superconductive elements



KNOWN SUPERCONDUCTIVE ELEMENTS

🟦 BLUE = AT AMBIENT PRESSURE

🟩 GREEN = ONLY UNDER HIGH PRESSURE

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	🟩 3 Li	🟦 4 Be											🟩 5 B	🟨 6 C	7 N	🟩 8 O	9 F	10 Ne
3	11 Na	12 Mg											🟦 13 Al	🟩 14 Si	🟩 15 P	🟩 16 S	17 Cl	18 Ar
4	19 K	🟩 20 Ca	🟩 21 Sc	🟦 22 Ti	🟦 23 V	24 Cr	25 Mn	🟩 26 Fe	27 Co	28 Ni	29 Cu	🟦 30 Zn	🟦 31 Ga	🟩 32 Ge	🟩 33 As	🟩 34 Se	🟩 35 Br	36 Kr
5	37 Rb	🟩 38 Sr	🟩 39 Y	🟦 40 Zr	🟦 41 Nb	🟦 42 Mo	🟦 43 Tc	🟦 44 Ru	🟦 45 Rh	46 Pd	47 Ag	🟦 48 Cd	🟦 49 In	🟦 50 Sn	🟩 51 Sb	🟩 52 Te	🟩 53 I	54 Xe
6	🟩 55 Cs	🟩 56 Ba	🟦 57 *La	🟦 72 Hf	🟦 73 Ta	🟦 74 W	🟦 75 Re	🟦 76 Os	🟦 77 Ir	🟦 78 Pt	79 Au	🟦 80 Hg	🟦 81 Tl	🟦 82 Pb	🟩 83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

SUPERCONDUCTORS.ORG

* Lanthanide Series	🟩 58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	🟩 71 Lu
+ Actinide Series	🟦 90 Th	🟦 91 Pa	🟦 92 U	93 Np	94 Pu	🟦 95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Transition temperatures

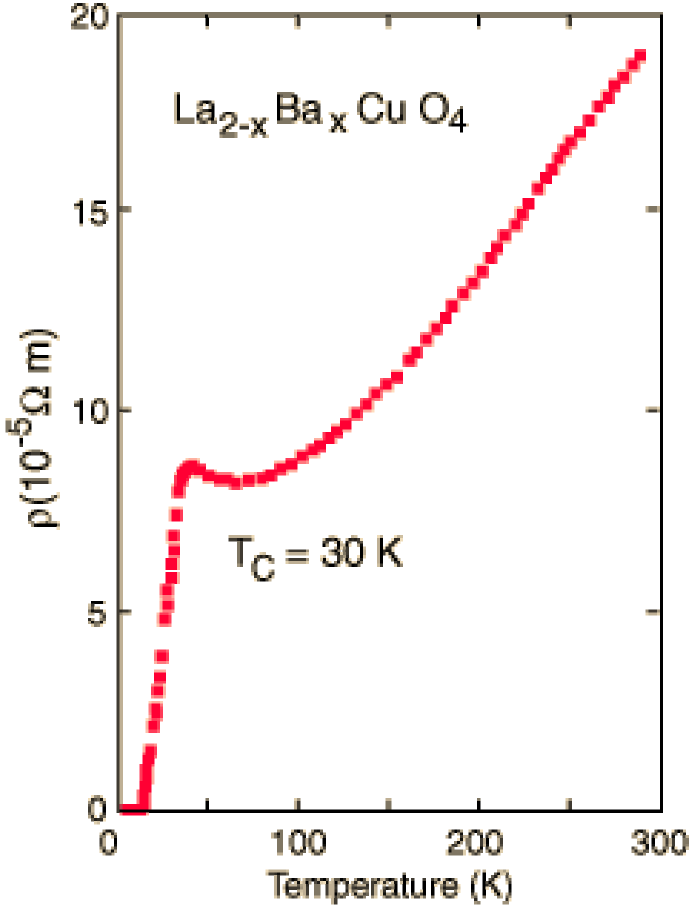
Nb	9.25K	BCC(Type 2)
Tc	7.80 K	HEX(Type 2)
Lead (Pb)	7.196 K	FCC
V	5.40 K	BCC(Type 2)
Lanthanum (La)	4.88 K	HEX
Tantalum(Ta)	4.47 K	BCC
Mercury (Hg)	4.15 K	RHL
Tin (Sn)	3.72 K	TET
Indium (In)	3.41 K	TET
Thallium (Tl)	2.38 K	HEX
Rhenium (Re)	1.697 K	HEX
Protactinium (Pa)	1.40 K	TET
Thorium (Th)	1.38 K	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	HEX
Tungsten (W)	0.0154 K	BCC
Platinum (Pt)*	0.0019 K	FCC
Rhodium (Rh)	0.000325 K	FCC

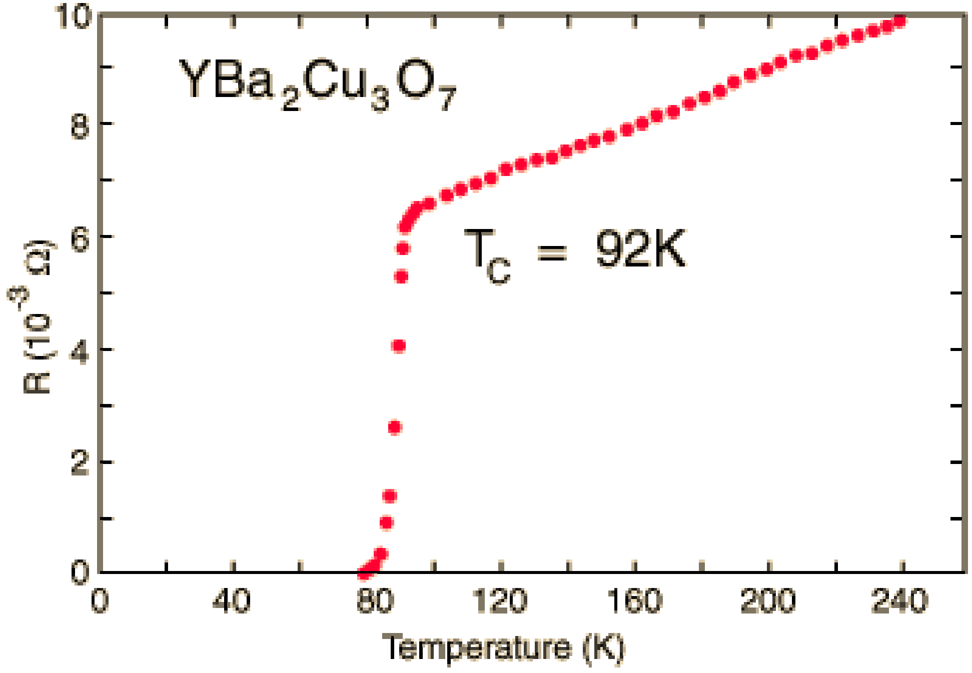
*compacted powder

MgB_2	39K
Nb_3Ge	23.2K

Transition temperature(Hi-Tc)



Bednorz and Muller, Z. Physik B64, 189, (1986)



M. K. Wu, et al., Phys. Rev. Lett. 58, 908 (1987)

VOLUME 58, NUMBER 9 PHYSICAL REVIEW LETTERS 2 MARCH 1987

Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure

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and

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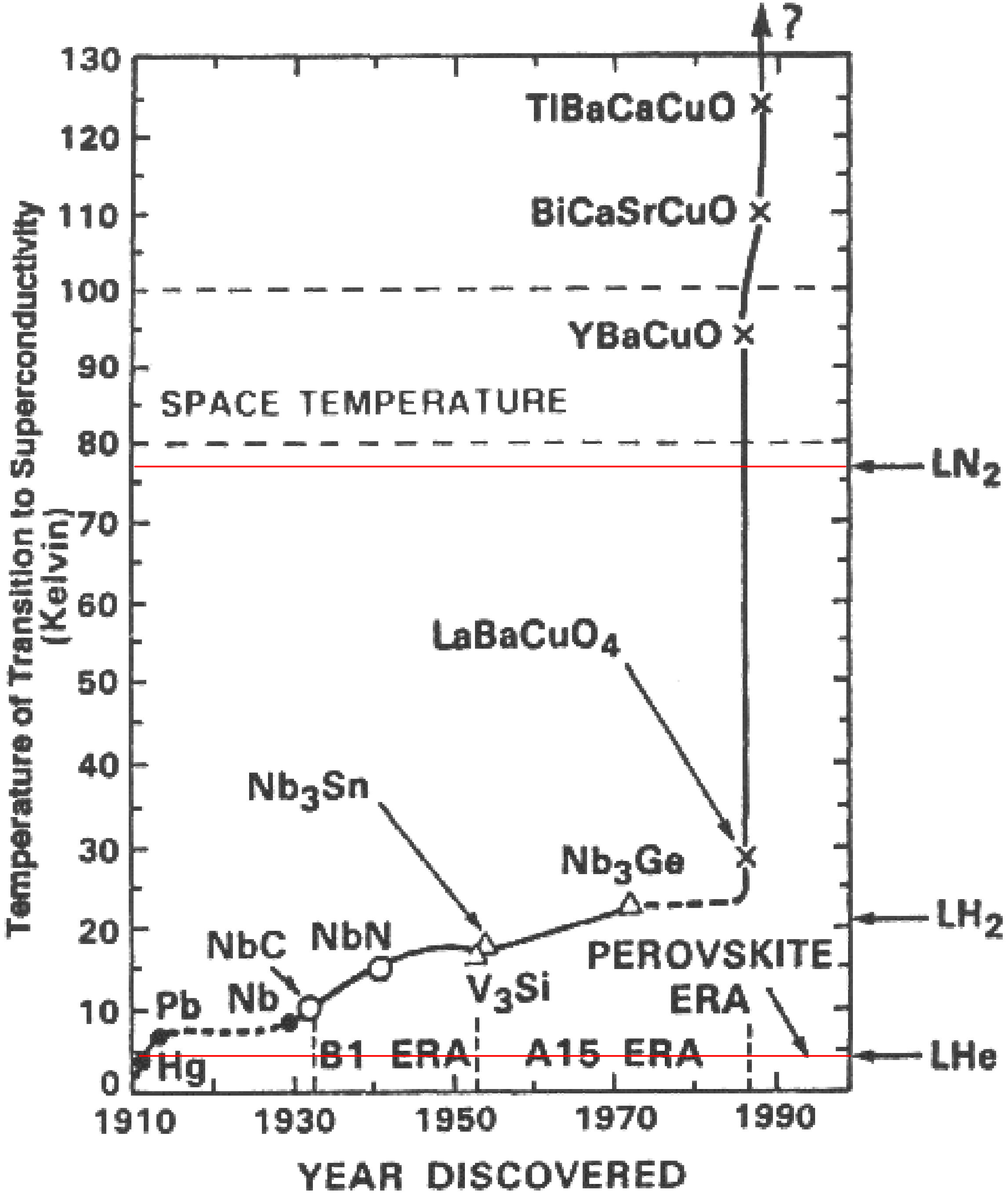
(Received 6 February 1987; Revised manuscript received 18 February 1987)

A stable and reproducible superconductivity transition between 80 and 93 K has been unambiguously observed both resistively and magnetically in a new Y-Ba-Cu-O compound system at ambient pressure. An estimated upper critical field $H_{c2}(0)$ between 80 and 180 T was obtained.

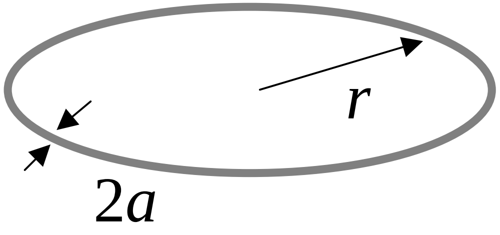
PACS numbers: 74.70.Ya


?
TlBaCaCuO
BiCaSrCuO
YBaCuO
SPACE TEMPERATURE
LaBaCuO4
Nb3Sn
Nb3Ge
NbC
NbN
Nb
Pb
Hg
V3Si
PERQVSKITE
ERA
B1 ERA
A15 ERA
LN2
LH2
LHe
Temperature of Transition to Superconductivity (Kelvin)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
1910
1930
1950
1970
1990
YEAR DISCOVERED

Persistent current

The inductance of the loop

$$L = \mu_0 r \left[\ln \frac{8r}{a} - 2 \right]$$



The resistance of the loop

$$R = \frac{2r\rho}{a^2}$$

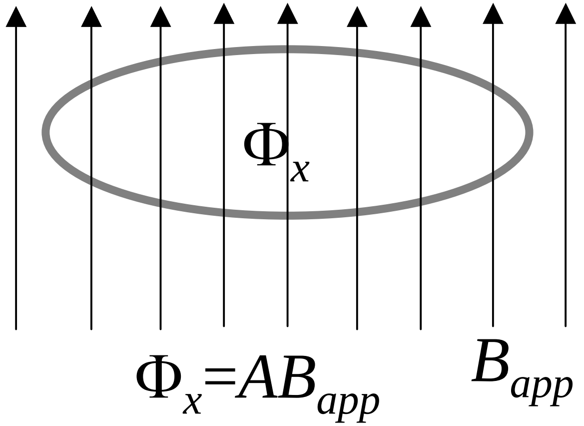
The time constant $\tau = L/R$ $i(t) = i(0)e^{-t/\tau}$

$\rho < 10^{-26}\ \Omega\ \mathrm{m}$

For Cu $\rho \sim 1.56\ \mu\Omega\ \mathrm{cm}$

Resistanceless circuit

The flux due to external field threading a closed loop $\Phi_x = AB_{app}$



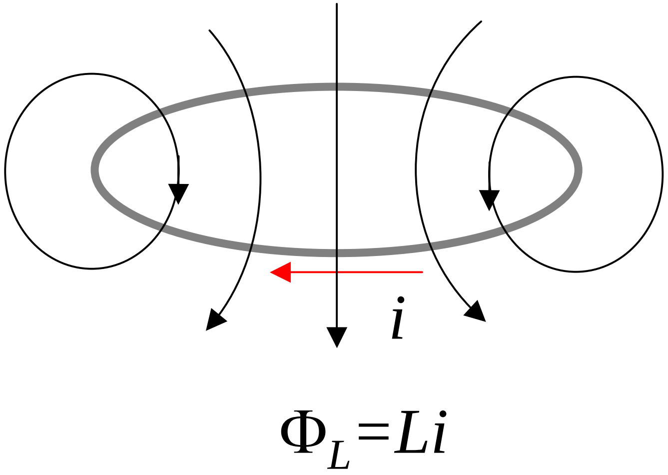
The induction law yields:

$$-A\frac{dB_a}{dt} = Ri + L\frac{di}{dt}$$

For a resistanceless loop:

$$-A\frac{dB_a}{dt} = L\frac{di}{dt}$$

$$\Rightarrow \quad Li + AB_a = \text{constant}$$



The total magnetic flux threading a closed loop $\Phi = \Phi_x + \Phi_L = \text{constant}$

Superconducting solenoid

The current is generated by the power supply P, and is adjusted by the rheostat R. Once the current is brought to the desired value, the switch XY can be closed. Since S and XY form a closed resistanceless loop, the magnetic field flux threaded by the loop remains the same. Now one can disconnect the power supply and the solenoid runs in the persistent mode.

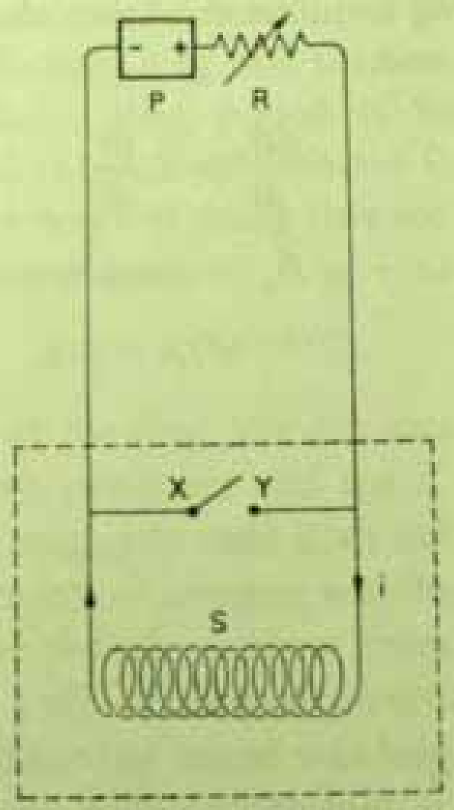


FIG. 1.5. Superconducting solenoid.

2. Perfect diamagnetism

Perfect diamagnetism

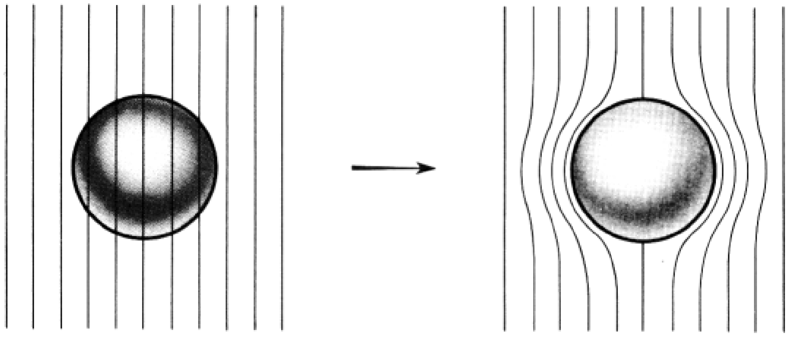
superconductor

Perfect diamagnetism

Flux exclusion: zero field cooled

Flux expulsion: field cooled

$B = 0$ Meissner effect



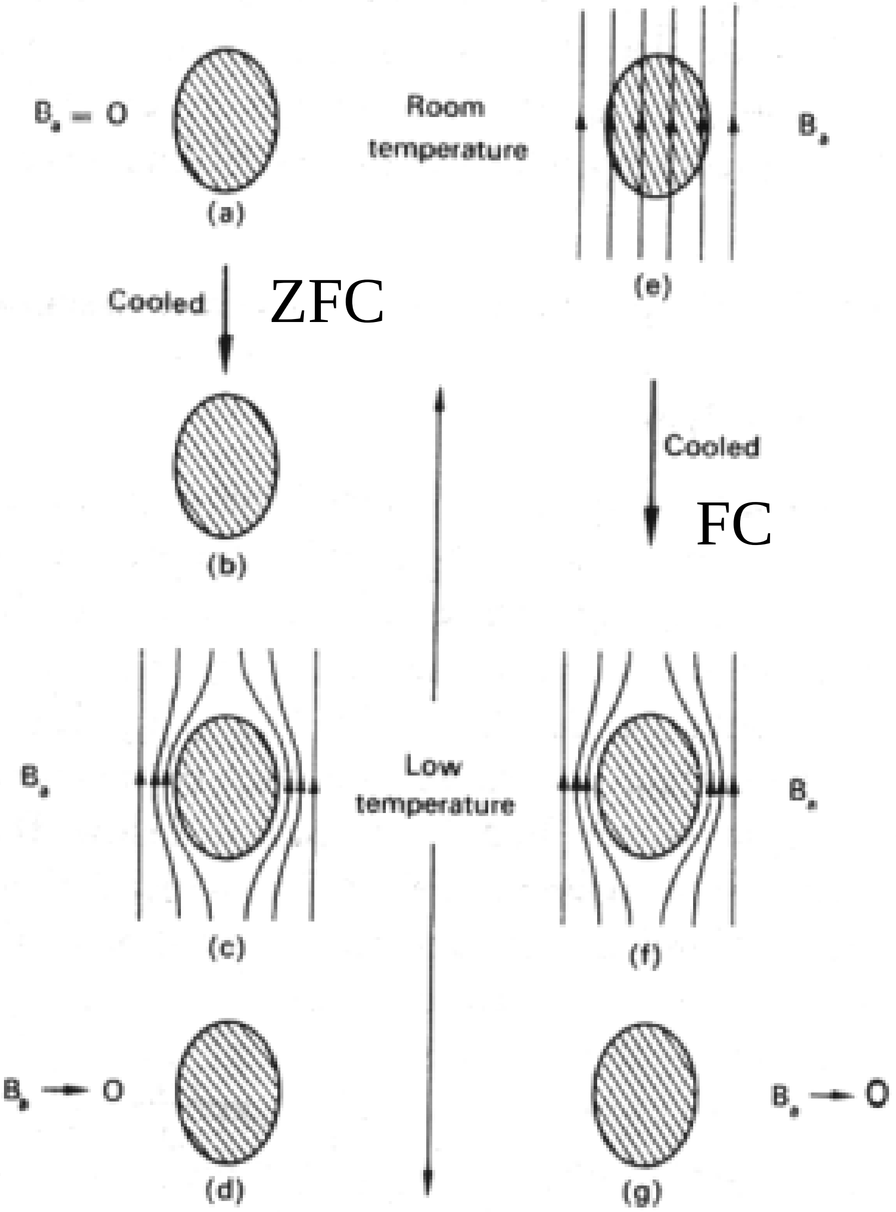
Perfect conductor

Constant magnetic flux

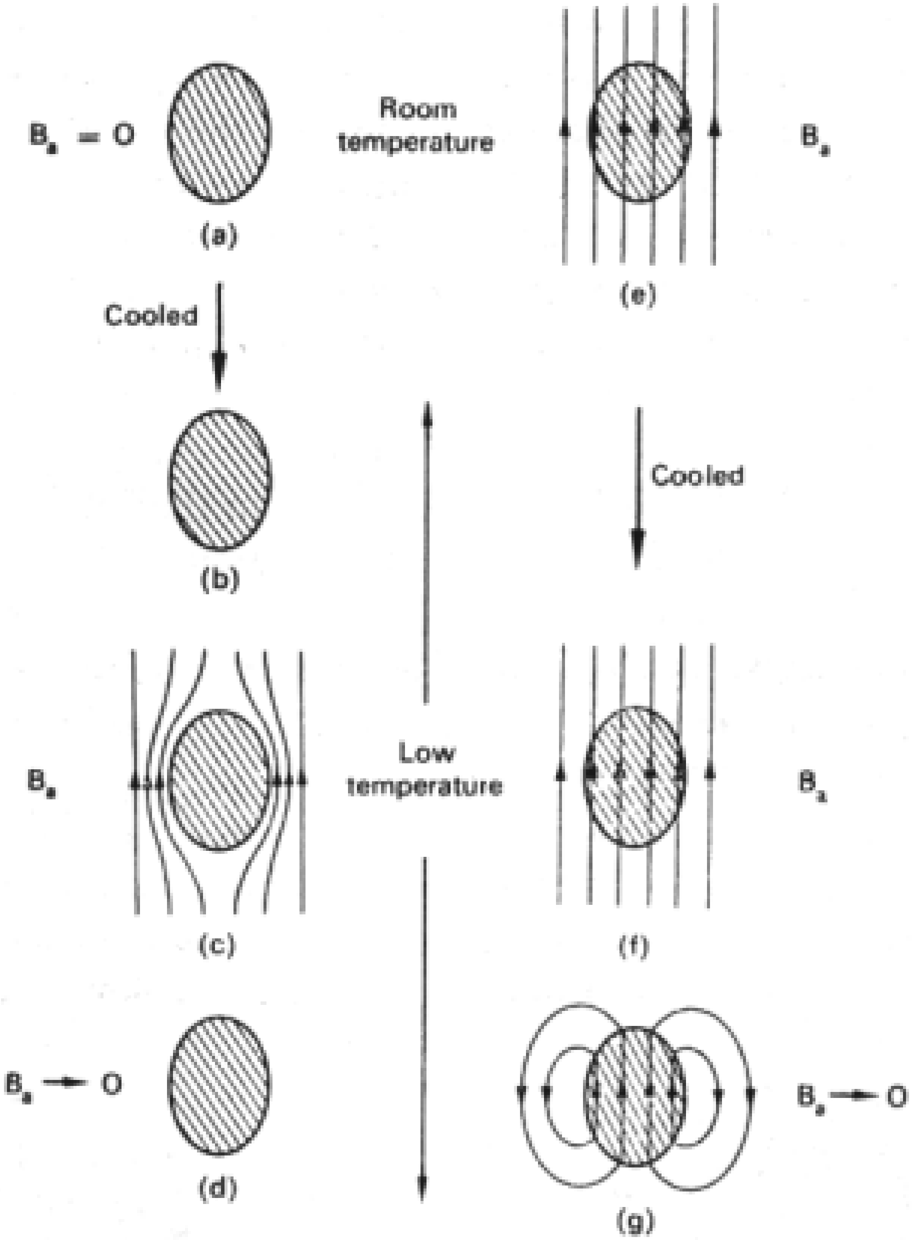
$\dot{B} = 0$

Recall the result deduced in page 14

superconductor



Perfect conductor



Permeability

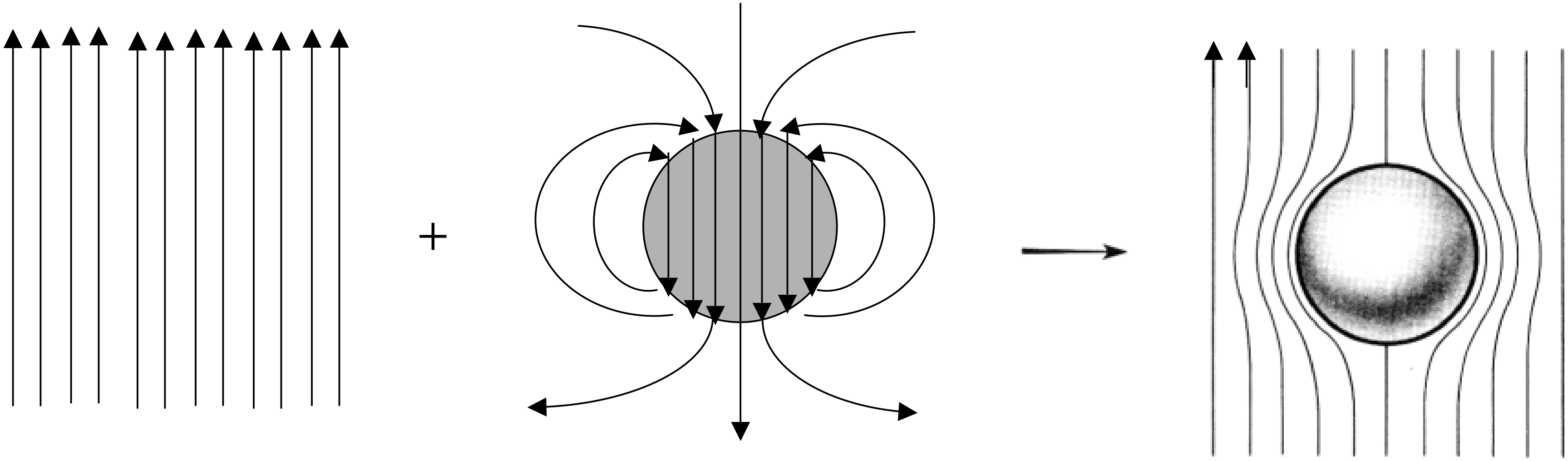
$$B = \mu_0 \left(H + M \right) = \mu_0 \left(1 + \chi \right) H$$

$$M = -H$$

Magnetic susceptibility

$$\chi = -1$$

Magnetic permeability $\mu = 0$



$B_{app} = \mu_0 H$

$M = -H$ (inside the sphere)

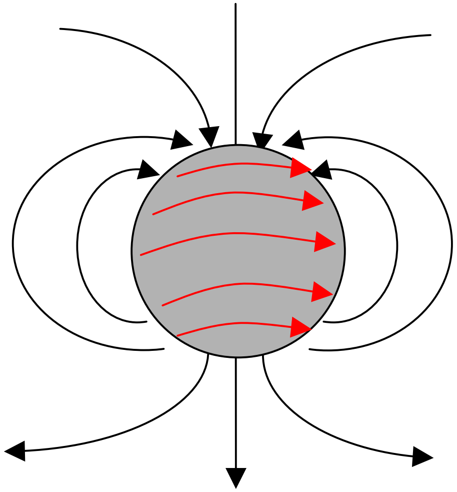
B

A dipole field outside the sphere

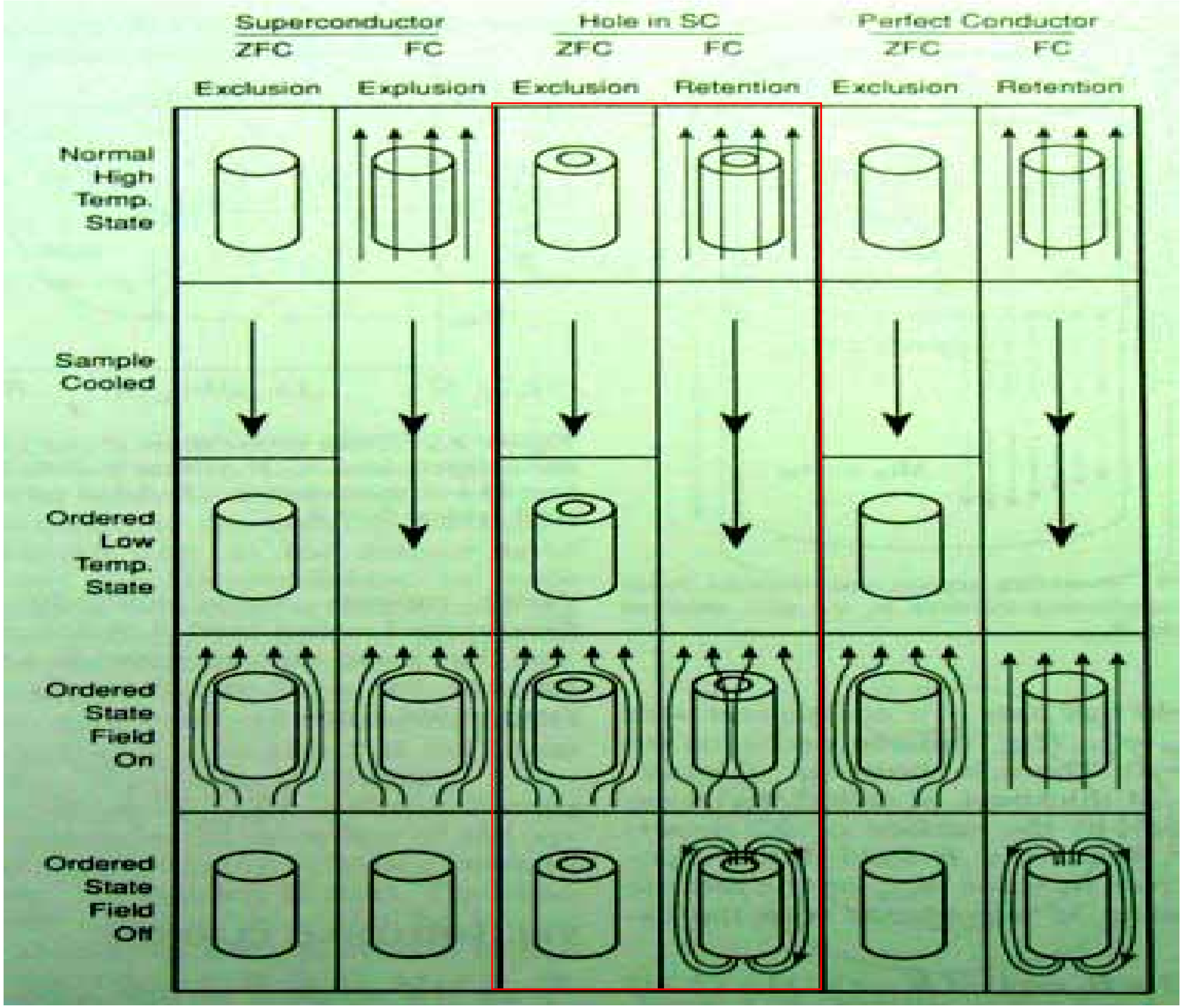
Surface currents

$$\nabla \times B = \mu_0 J$$

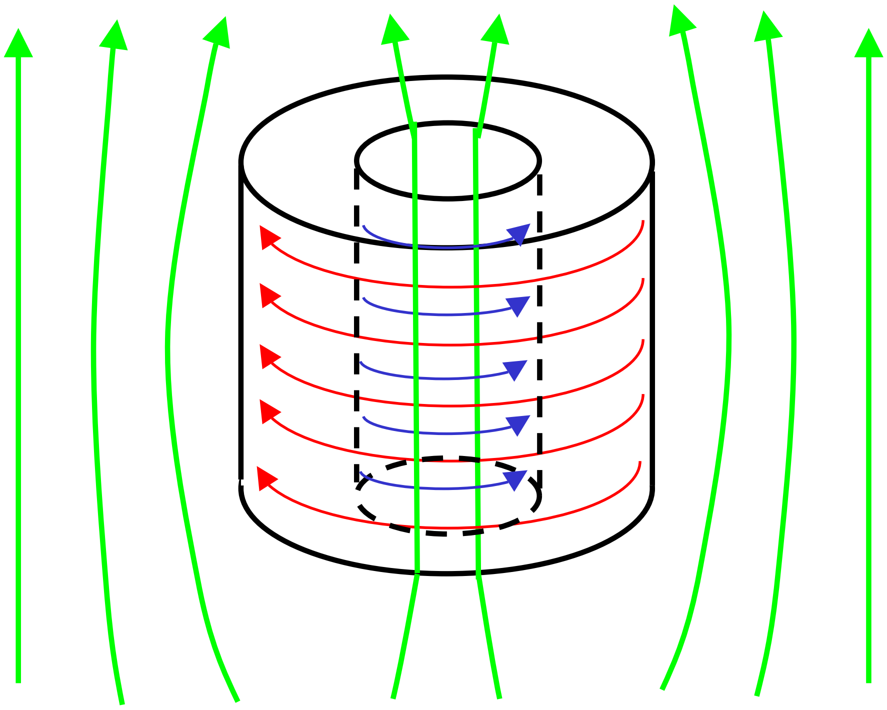
$$J = \nabla \times M$$



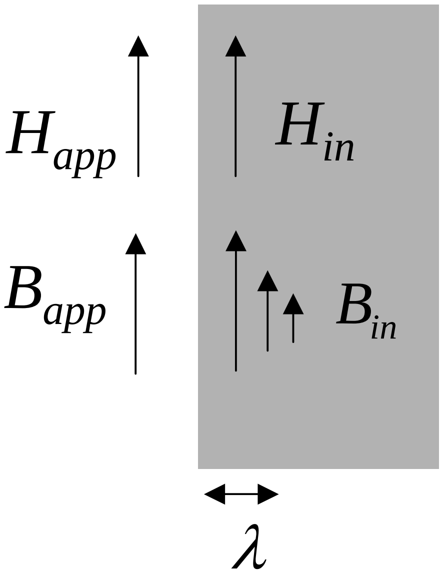
Hole in Superconductor



Surface currents



Penetration depth



Boundary condition

$$H'_{\parallel} = H''_{\parallel}$$

$$H_{app} = H_{in}$$

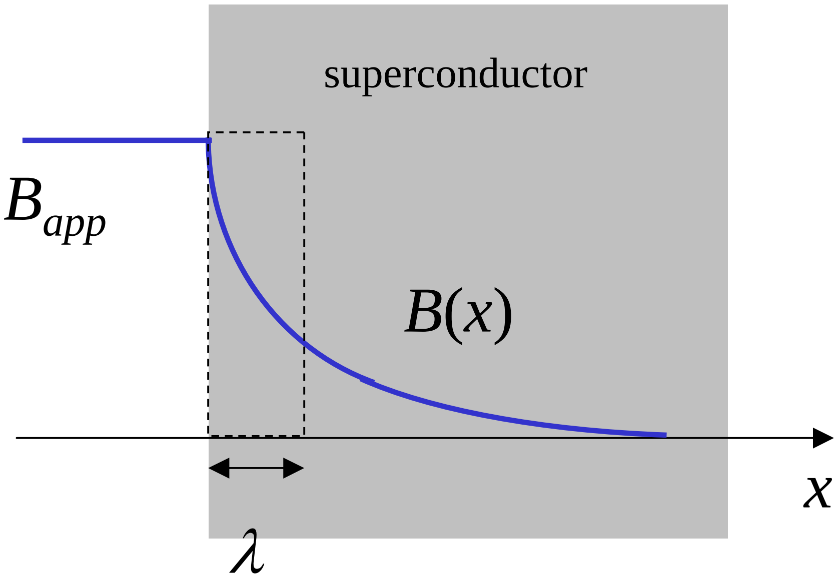
For perfect diamagnetism

$$B_{app} = \mu_0 H_{app} \qquad B_{in} = 0$$

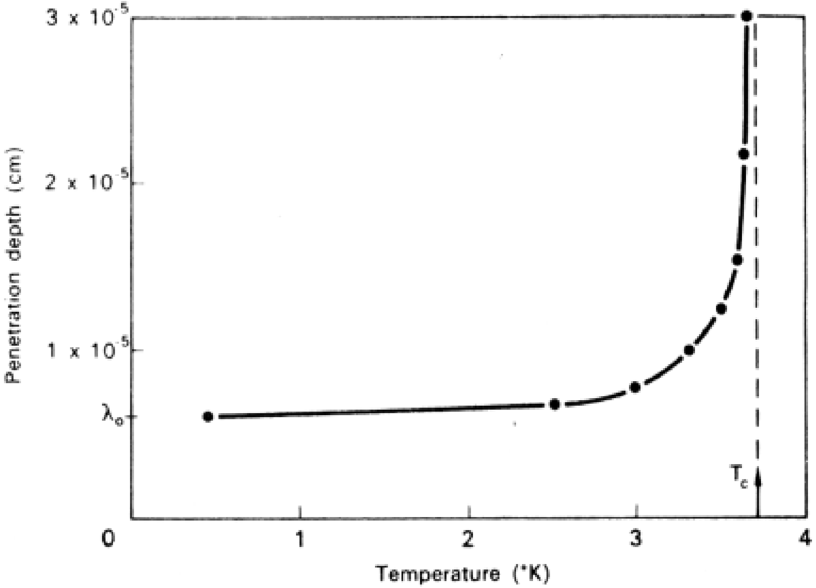
For a finite current density, the surface current is distributed within a depth, λ

London theory

$$B(x) = B(0)e^{-x/\lambda}$$

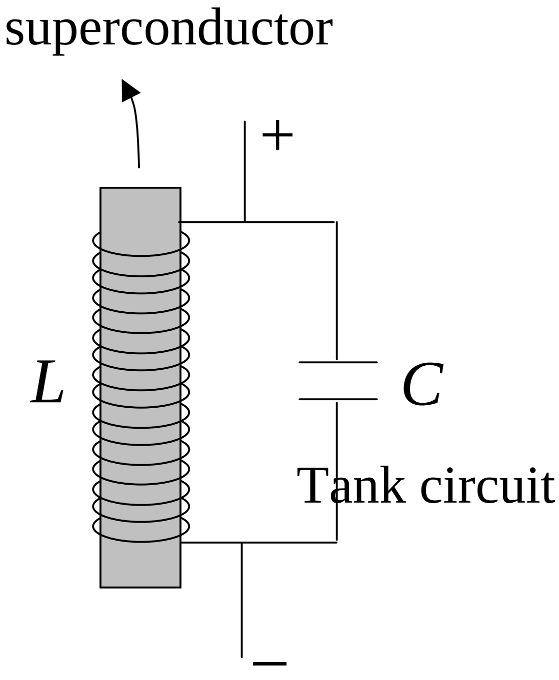


Variation with temperature



$$\frac{\lambda}{\lambda_0} = \frac{1}{\left(1 - t^4\right)^{1/2}}$$

$$t = T/T_C$$



The measurement of penetration depth

Self inductance of the solenoid, *L* is a function of penetration depth

The tank circuit form an oscillator of a typical frequency