Condensed Matter Physics

Superconductivity

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- ☞ *Occurrence of Superconductivity*
- ☞ *Destruction of Superconductivity by Magnetic Fields*
- ☞ *Meissner Effect*
- ☞ *TYPE I & TYPE II SCs*

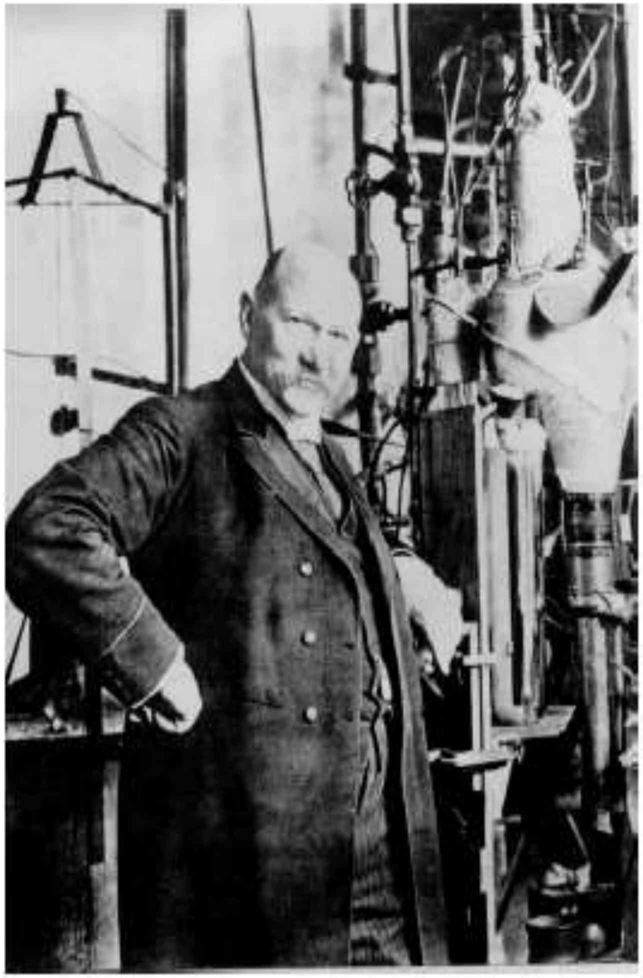
Superconductivity

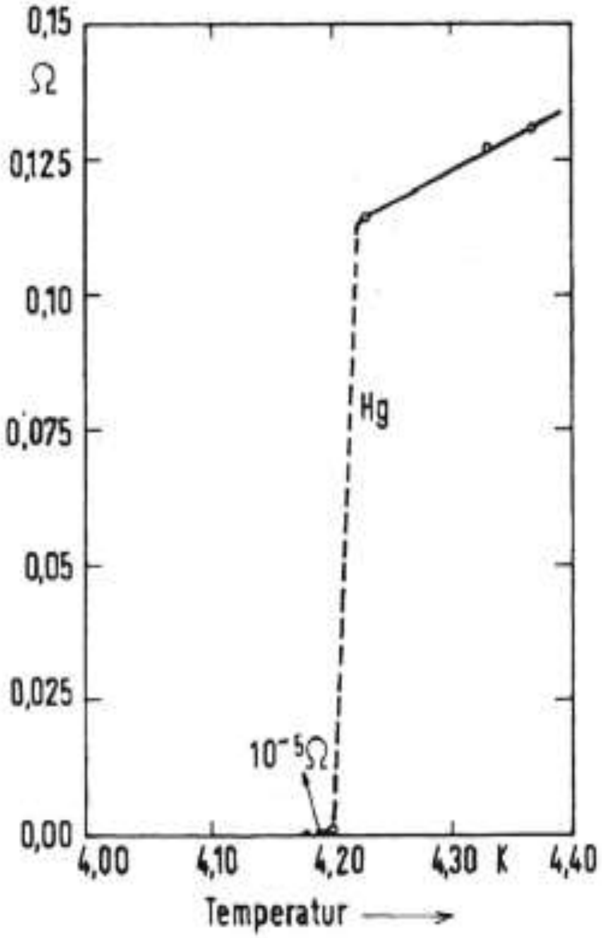
K.Onnes (1911) :

$$\rho \rightarrow 0 \quad \text{as} \quad T \rightarrow T_C$$

Superconductivity was discovered by Kamerlingh-Onnes in 1911 in mercury (Hg), having $T_c \approx 4$ K

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





Dependence of the resistance on temperature

SUPERCONDUCTIVITY

Superconductivity is one of the most important area of solid state chemistry

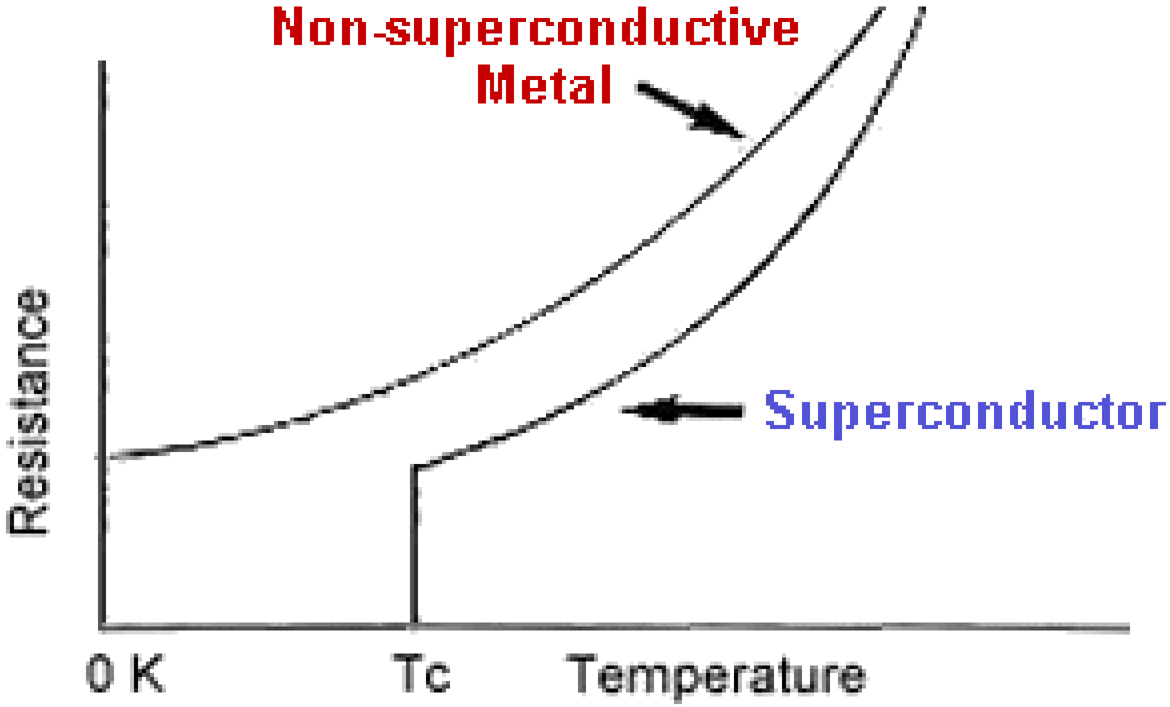
Superconductors have two technologically important properties:

ZERO ELECTRICAL RESISTANCE

Superconductors carry current without energy loss

PERFECT DIAMAGNETISM

Superconductors float (levitate) above magnetic fields



R=0, below T_c

Perfect diamagnetism

Historic Milestones

- 1908 Making liquid helium (4.2 K)
- ● 1911 Discovery of zero resistance
- ● 1933 Meissner effect
- 1935 Londons' theory
- ● 1950 Ginzburg-Landau theory
- ● 1957 Bardeen-Cooper-Schrieffer (BCS) theory
- 1960 Magnetic flux quantization
- ● 1962 Josephson effect
- ● 1986 High-temperature superconductors

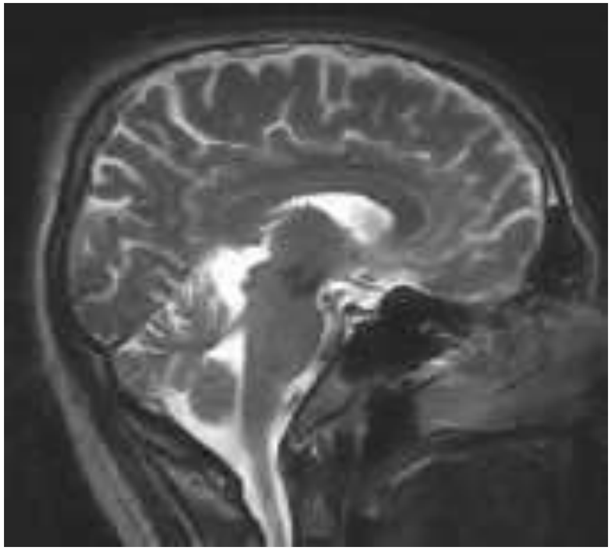
● Nobel Prizes

APPLICATIONS OF SUPERCONDUCTORS

The wide applicability of superconductors is due to

- Diamagnetism
- Zero resistance
- Higher current

Medical Industry



MRI Exploits the high magnetic fields expelled by superconducting wires for medical applications

Since the superconducting coils are capable of producing very stable, large magnetic field strengths, they generate high quality images.

Transportation Industry

Superconductor coils create strong magnetic fields that produce the effect of levitation by repulsion

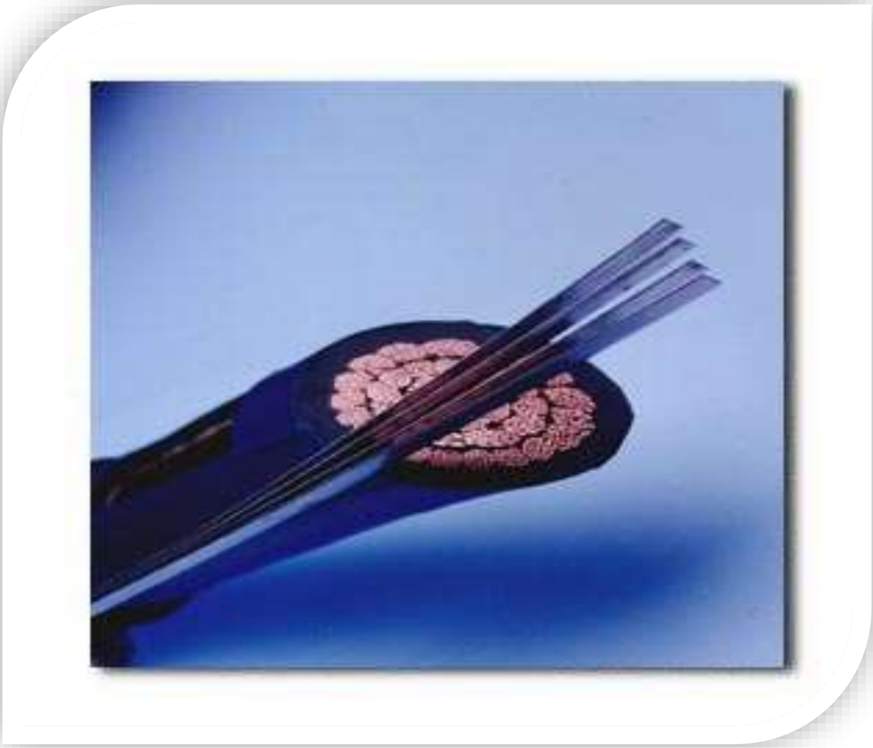
Maglev trains hover above a magnetic field without any contact with the tracks

As a result, high speeds of up to 500 miles per hour are possible with only a small consumption of energy

Electric Power Industry

High temperature superconductors (HTS) can be used in the production of more cost effective motors and generators

HTS power cables can carry two to ten times more power in equally or smaller sized cables

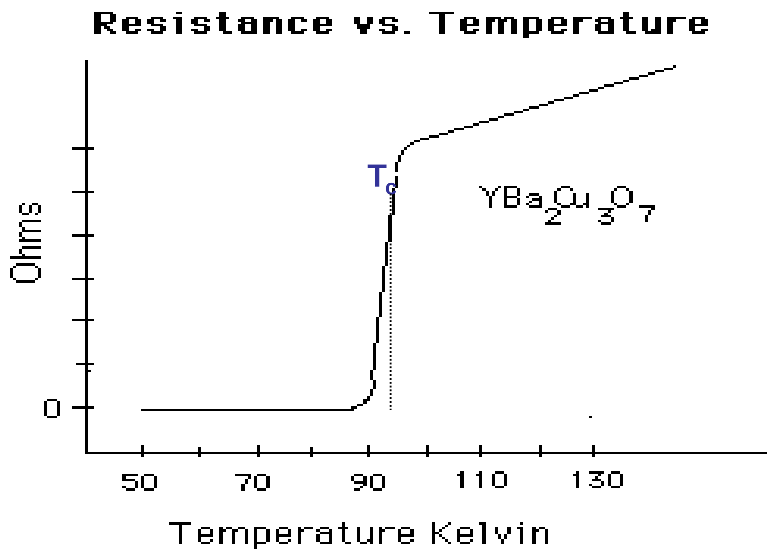


FUNDAMENTAL PROPERTIES OF SUPERCONDUCTORS

Superconductors are characterized by three fundamental properties

T_c

Transitions from normal state to the superconducting state occur at a ***Critical Temperature*** (T_c).



J_c

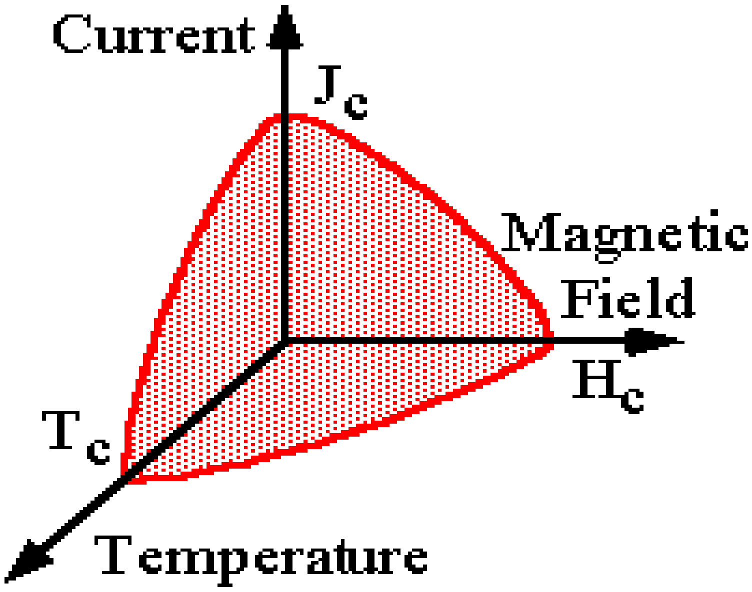
The ***Critical Current Density*** (**J_c**) is the maximum current that a superconductor can carry. Above J_c the normal state is re-installed

H_c

A superconductor in a magnetic field, at $T<T_c$ expels the magnetic field (Meissner effect)

If the external magnetic field is increased to a critical point (**H_c**) it penetrates the superconductor and re-instate the normal state

The ***critical magnetic field*** (**H_c**) is the value of the applied magnetic field for which a transition from superconducting to normal state is induced



A superconducting material exhibits superconductivity only below its critical temperature T_c, its critical magnetic field H_c,and its critical current density J_c.

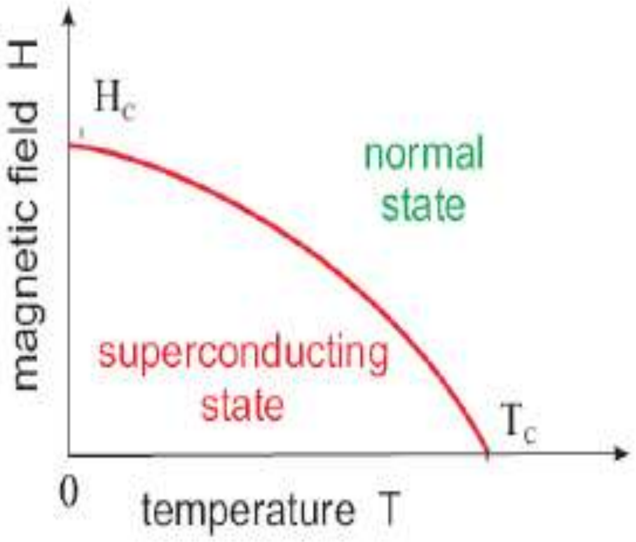
FUNDAMENTAL PROPERTIES OF SUPERCONDUCTORS

Superconductivity is destroyed:

- by increasing temperature at $T > T_c$
- by large magnetic field $H > H_c$

Phase diagram of a superconductor in the $H - T$ plane is described by an empirically found formula:

$$\frac{H_c(T)}{H_c(0)} = \left[1 - \left(\frac{T}{T_c}\right)^2\right]$$



$H - T$ diagram for the superconducting state

Occurrence of Superconductivity

Occurrence:

Metallic elements, alloys, intermetallic compounds,
doped semiconductors, organic metals, …

Range of T_C :

90K for $YBa_2Cu_3O_7$.

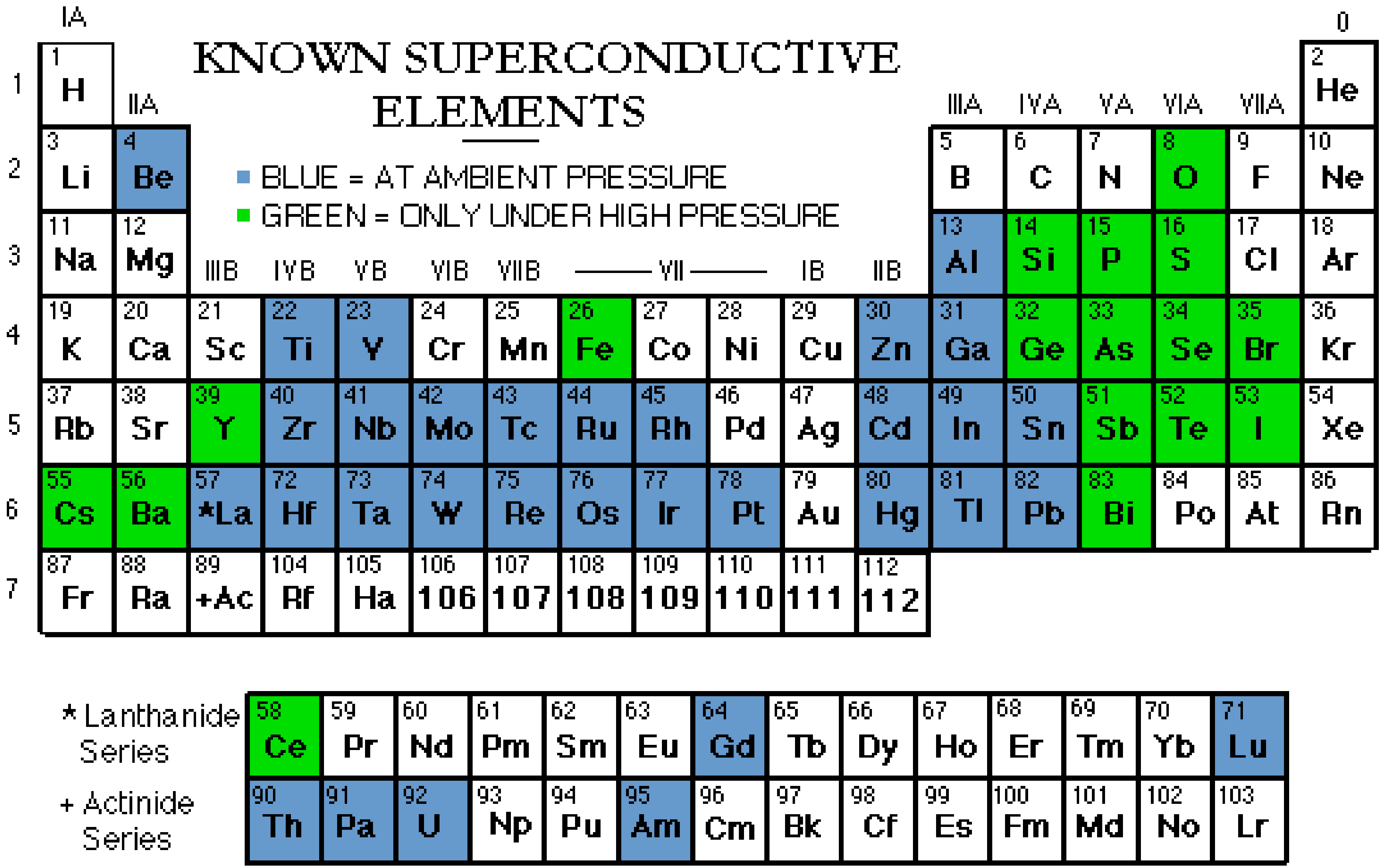
.001K for Rh.

Si: T_C = 8.3K at P = 165 Kbar

Table 2 Superconductivity of selected compounds

Compound	T_c, in K	Compound	T_c, in K
Nb_3Sn	18.05	V_3Ga	16.5
Nb_3Ge	23.2	V_3Si	17.1
Nb_3Al	17.5	$YBa_2Cu_3O_{6.9}$	90.0
NbN	16.0	Rb_2CsC_{60}	31.3
C_{60}	19.2	MgB_2	39.0

Occurrence of Superconductivity



Occurrence of Superconductivity

	material	T_c,K	H_c,Oe	year
pure metals	Al	1.2	105	1933
	In	3.4	280	
	Sn	3.7	305	
	Pb	7.2	803	1913
	Nb	9.2	2060	1930
alloys	NbN	15	$1.4\ 10^5$	1940
	Nb_3Ge	23	$3.7\ 10^5$	1971

Cold liquids required for reaching low temperatures:

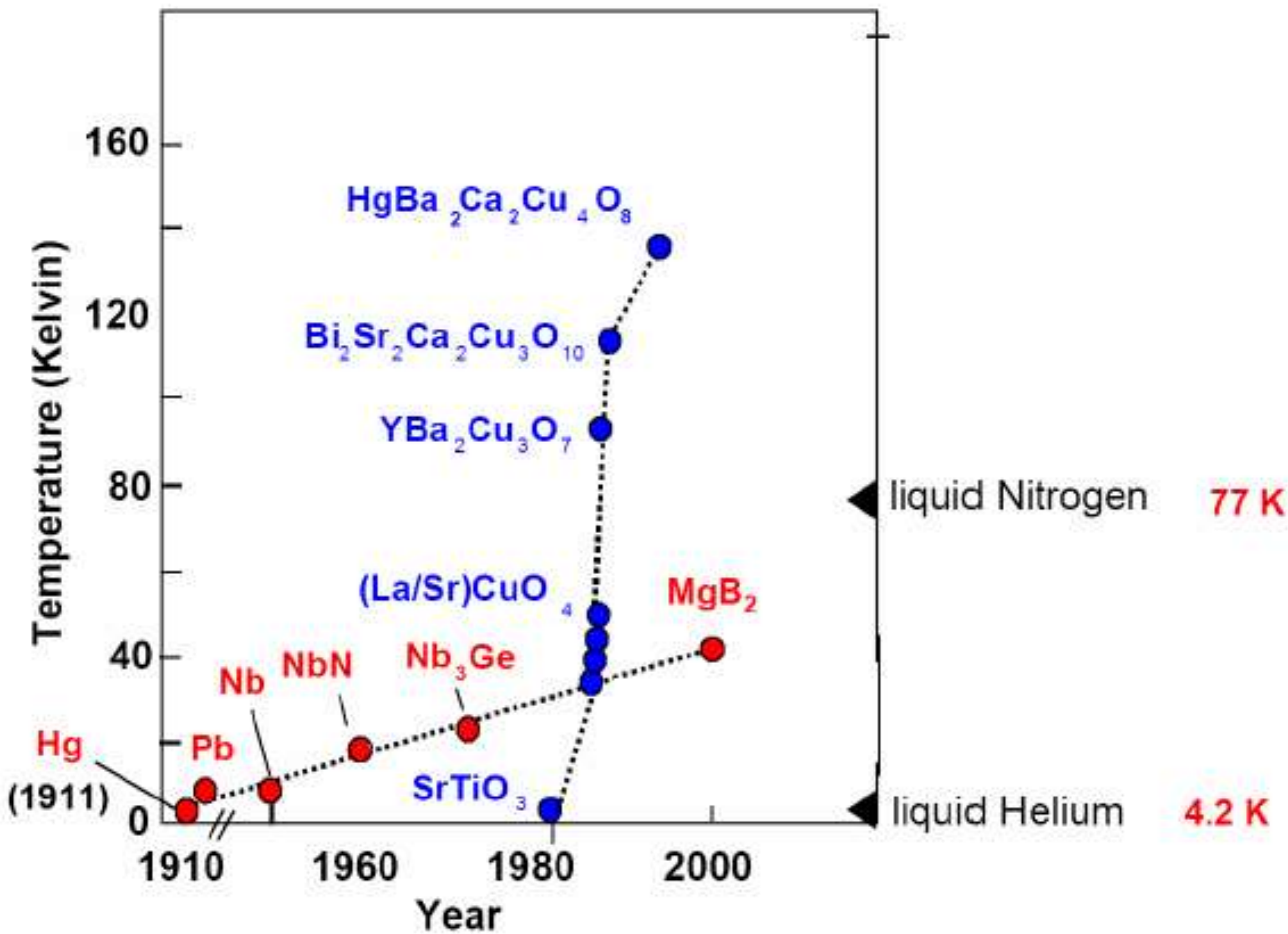
helium ^4He (4.2 K)
hydrogen H_2 (20 K)
neon Ne (27 K)
nitrogen N_2 (77 K)

ceramics

material	T_c,K	year
$La_{1.85}Ba_{0.15}CuO_4$	35	1986
$YBa_2Cu_3O_7$	93	1987
$Bi_2Sr_2CaCu_2O_{8+x}$	94	1988
$Ta_2Ba_2Ca_2Cu_3O_{10+x}$	125	1988
$HgBa_2Ca_2Cu_3O_{8+x}$	150^*	1993

* under pressure

Occurrence of Superconductivity

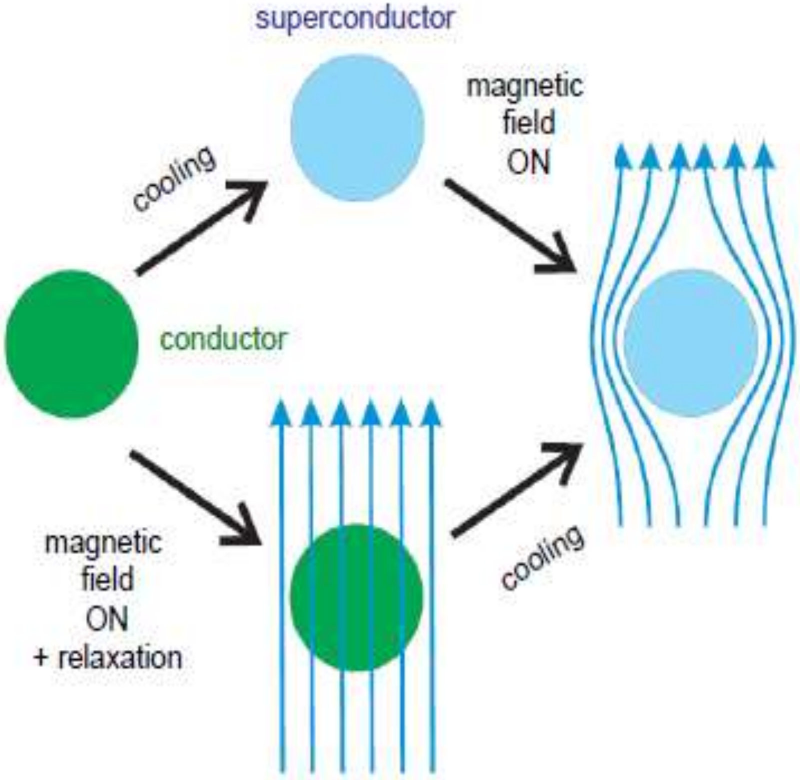


Meissner Effect

Example 3: finally, a superconductor

Meissner effect:

Superconductor always expels the magnetic flux

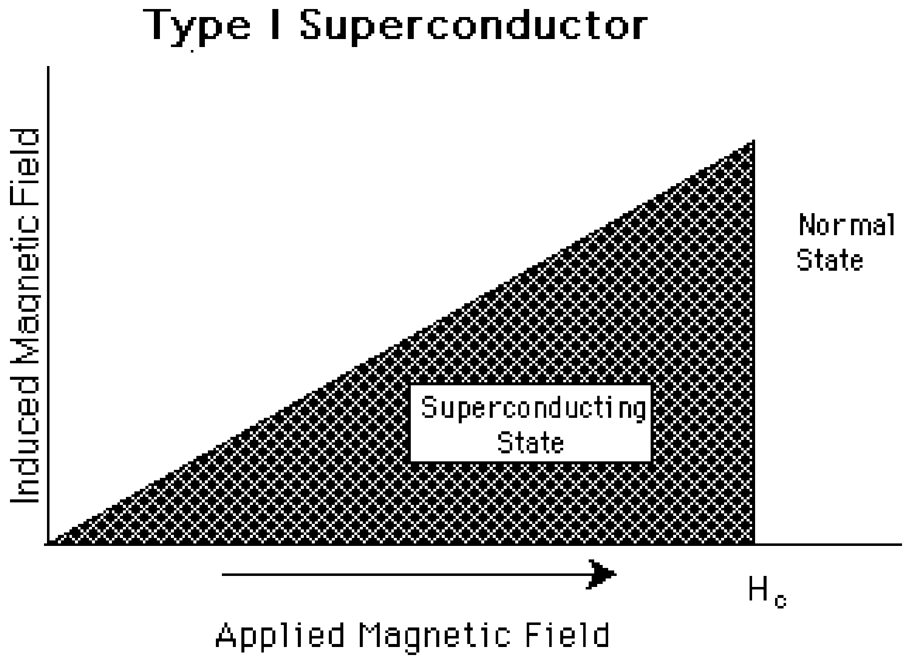


A superconductor in magnetic field

TYPES OF SUPERCONDUCTORS

There are two types of superconductors, Type I and Type II, according to their behaviour in a magnetic field

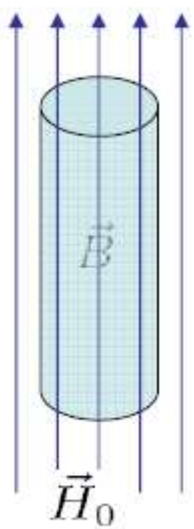
Type I



Type 1 superconductors show an abrupt transition from superconducting to normal state or vice-versa)

Type I superconductors are pure metals and alloys

TYPE I SUPERCONDUCTORS



Magnetization curve

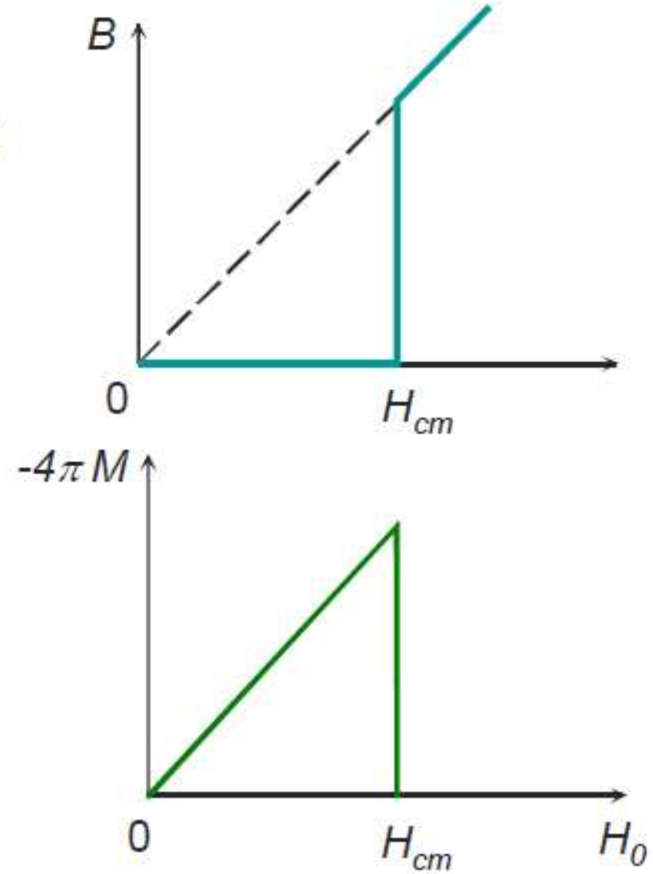
$$\boxed{\vec{B} = \vec{H}_0 + 4\pi\vec{M}} \quad \text{[cgs]}$$

$$\vec{B} = \mu_0(\vec{H}_0 + \vec{M}) \quad \text{[SI]}$$

$\vec{B}$ magnetic induction

$\vec{H}_0$ magnetic field intensity

$\vec{M}$ magnetic moment per unit volume



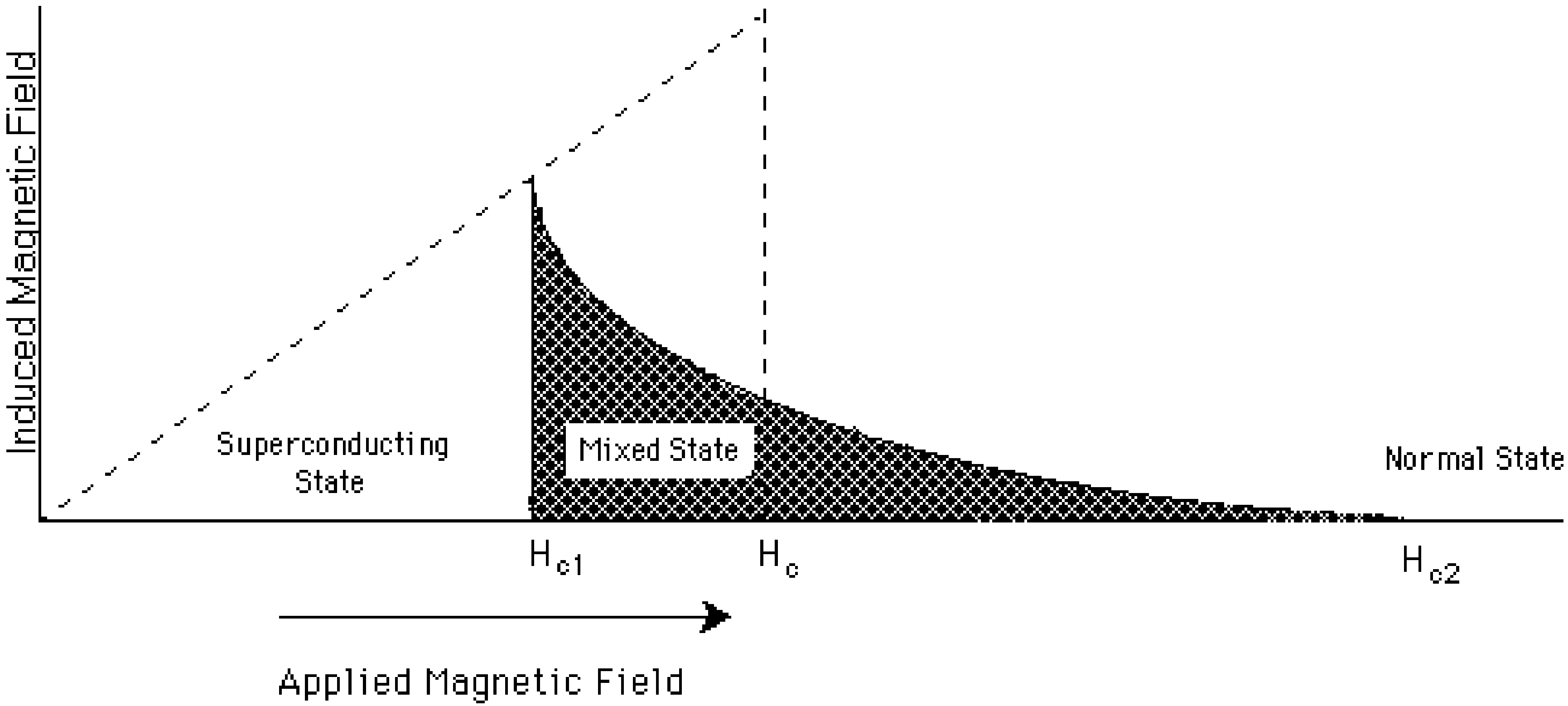
Magnetic properties can be derived from

main equations for the superconducting state:

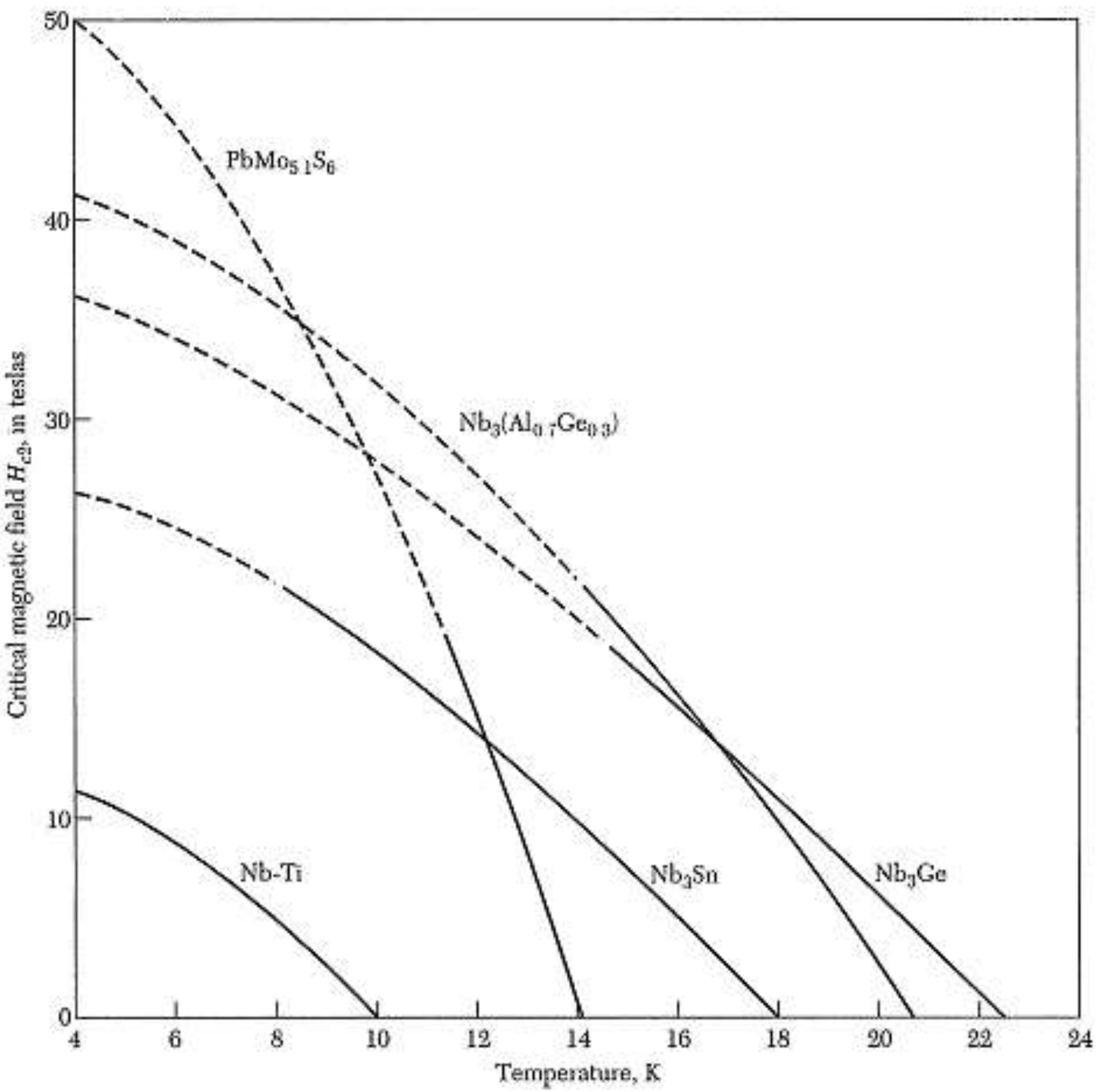
$$\begin{cases} \rho = 0 \\ \vec{B} = 0 \end{cases}$$

Type-I are all elements-superconductors except Nb

TYPE II SUPERCONDUCTORS



Type 2 superconductors show a gradual transition from superconducting to normal state or vice-versa



H_{C2} ~ 41T for $Nb_3(Al_{0.7}\ Ge_{0.3})$.
H_{C2} ~ 54T for $PbMo_6S_8$.

Commercial superconducting magnets of ~1T are readily available.