MATR 4347

SUPERCONDUCTOR CERAMICS

WHAT'S A SUPERCONDUCTOR?

Superconductors have two outstanding features:

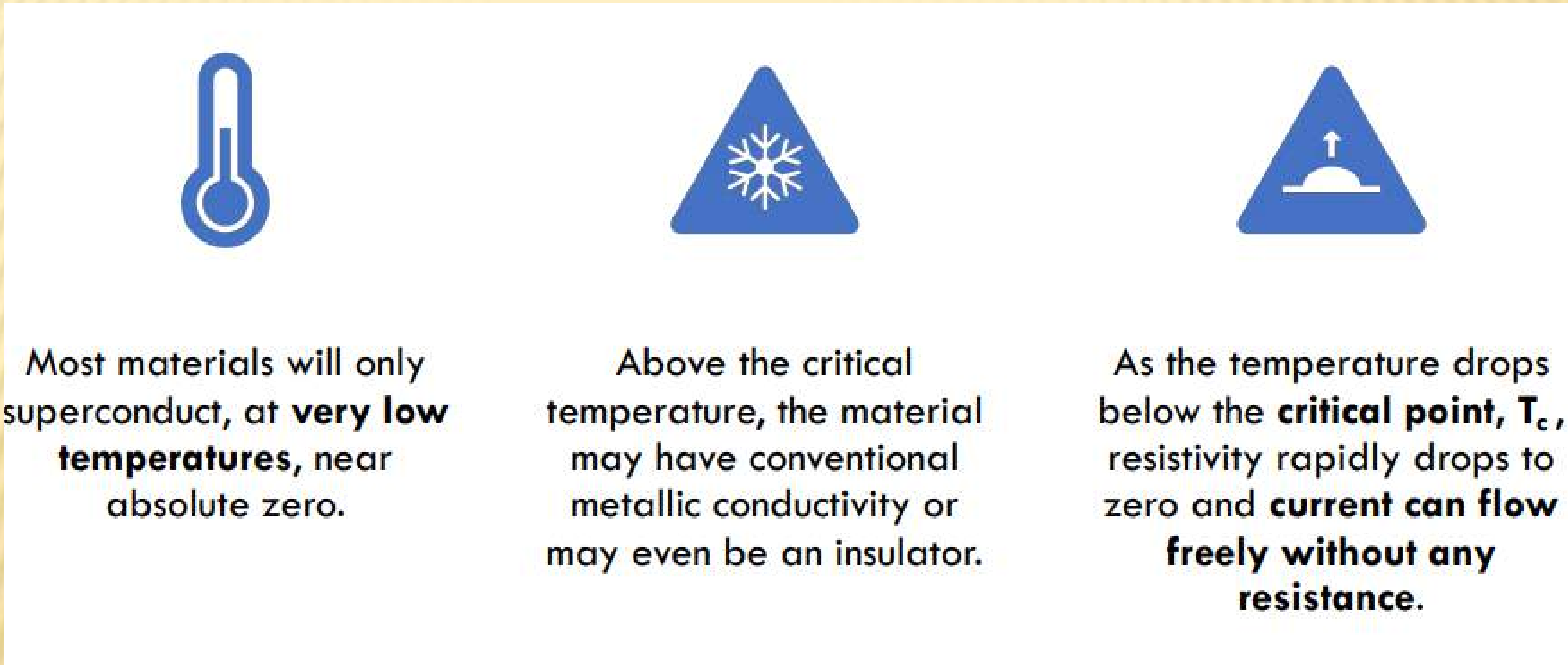
1). Zero electrical resistivity.

- This means that an electrical current in a superconducting ring continues indefinitely until a force is applied to oppose the current.

2). The magnetic field inside a bulk sample is zero (the Meissner effect).

- When a magnetic field is applied current flows in the outer skin of the material leading to an induced magnetic field that exactly opposes the applied field.
- The material is strongly diamagnetic as a result.
- In the Meissner effect experiment, a magnet floats above the surface of the superconductor

WHAT'S A SUPERCONDUCTOR?



WHAT'S A SUPERCONDUCTOR?

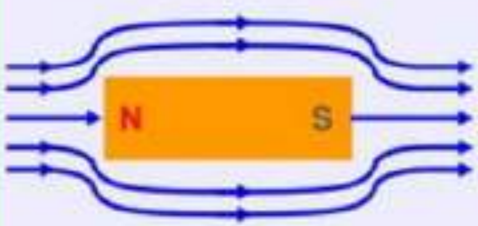
Superconductivity is a **phenomenon** of the flow of a current in certain materials with exactly zero electrical resistance when cooled below a characteristic critical temperature.

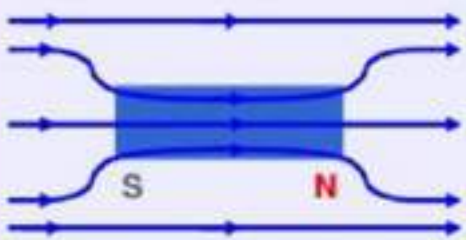
Superconductors are the **materials** having almost zero resistivity and behave as diamagnetic below the superconducting transiting temperature.

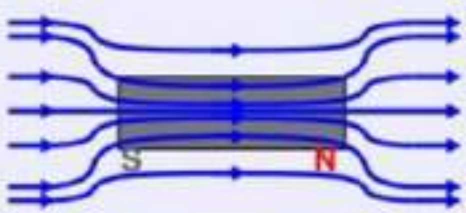
Diamagnetic materials are repelled by a magnetic field; an applied magnetic field creates an induced magnetic field in them in the opposite direction, causing a repulsive force.

DIAMAGNETIC MATERIALS

DIA	PARA	FERRO
1. Diamagnetic substances are those substances which are feebly repelled by a magnet. Eg. Antimony, Bismuth, Copper, Gold, Silver, Quartz, Mercury, Alcohol, water, Hydrogen, Air, Argon, etc.	Paramagnetic substances are those substances which are feebly attracted by a magnet. Eg. Aluminium, Chromium, Alkali and Alkaline earth metals, Platinum, Oxygen, etc.	Ferromagnetic substances are those substances which are strongly attracted by a magnet. Eg. Iron, Cobalt, Nickel, Gadolinium, Dysprosium, etc.
2. When placed in magnetic field, the lines of force tend to avoid the substance.	The lines of force prefer to pass through the substance rather than air.	The lines of force tend to crowd into the specimen.







PRINCIPLES

- Superconductor principles can be explained by examining various formulas.
- Lack of resistance in a current-carrying superconductor can be illustrated by:

Ohm's law, R=V/I

(R -resistance, V -voltage, I –current)

- Since superconducting materials carry current with no applied voltage, R=0.
- Superconductivity also does not involve power loss, since power is defined:

$$P=I^2R$$

- Since R is zero in superconducting material→power loss is zero.

- https://www.youtube.com/watch?time_continue=5&v=fuloQcIjFOs

WHAT'S A SUPERCONDUCTOR?

Linear reduction in resistivity as temperature is decreased:

- $\rho = \rho_o (1 + \alpha(T-T_o))$

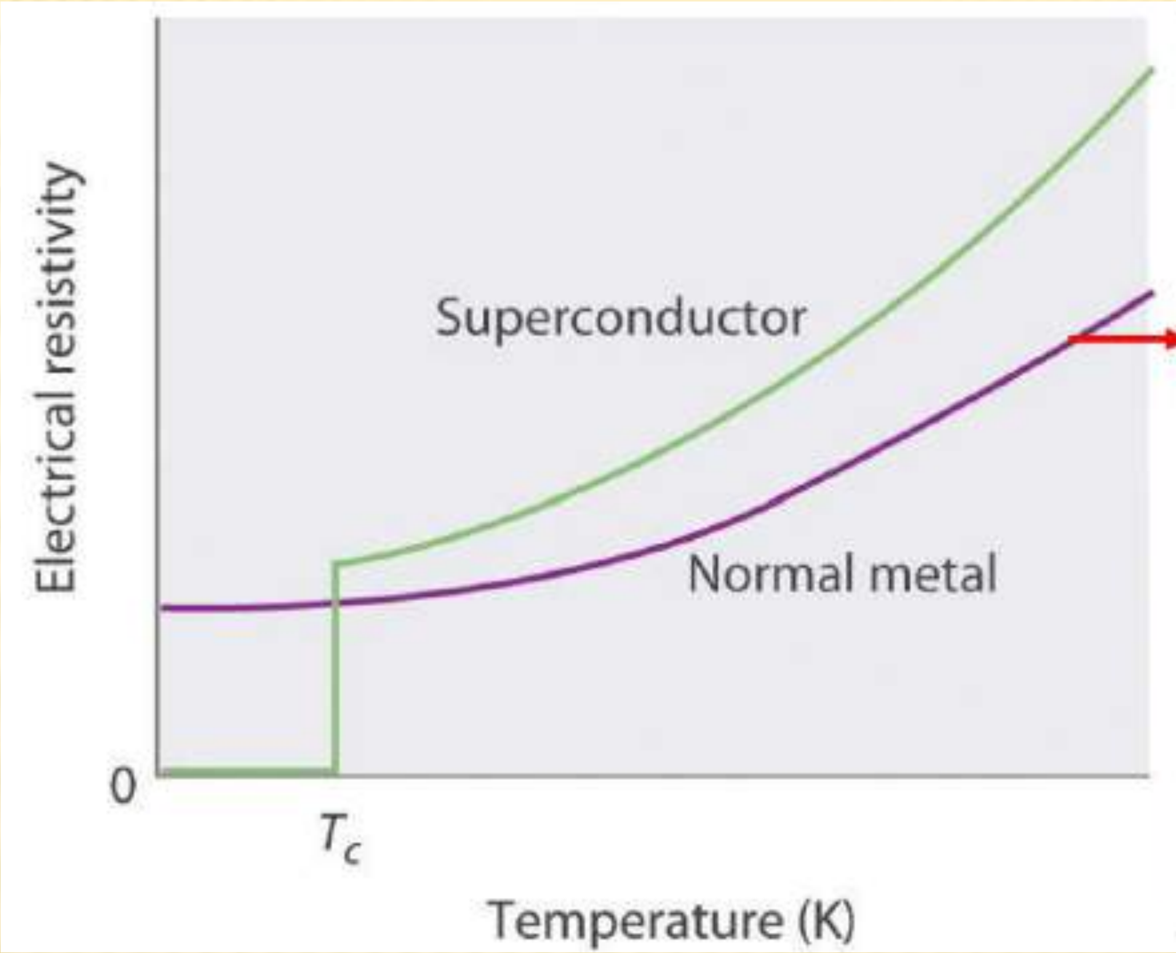
ρ: resistivity

α: the linear temperature coefficient of resistivity.

Resistivity for superconductor : $\rho_s \sim 4x10^{-23}\ \Omega$ cm

Resistivity for non-superconductor (metal) : $\rho_m \sim 1x10^{-13}\ \Omega$ cm

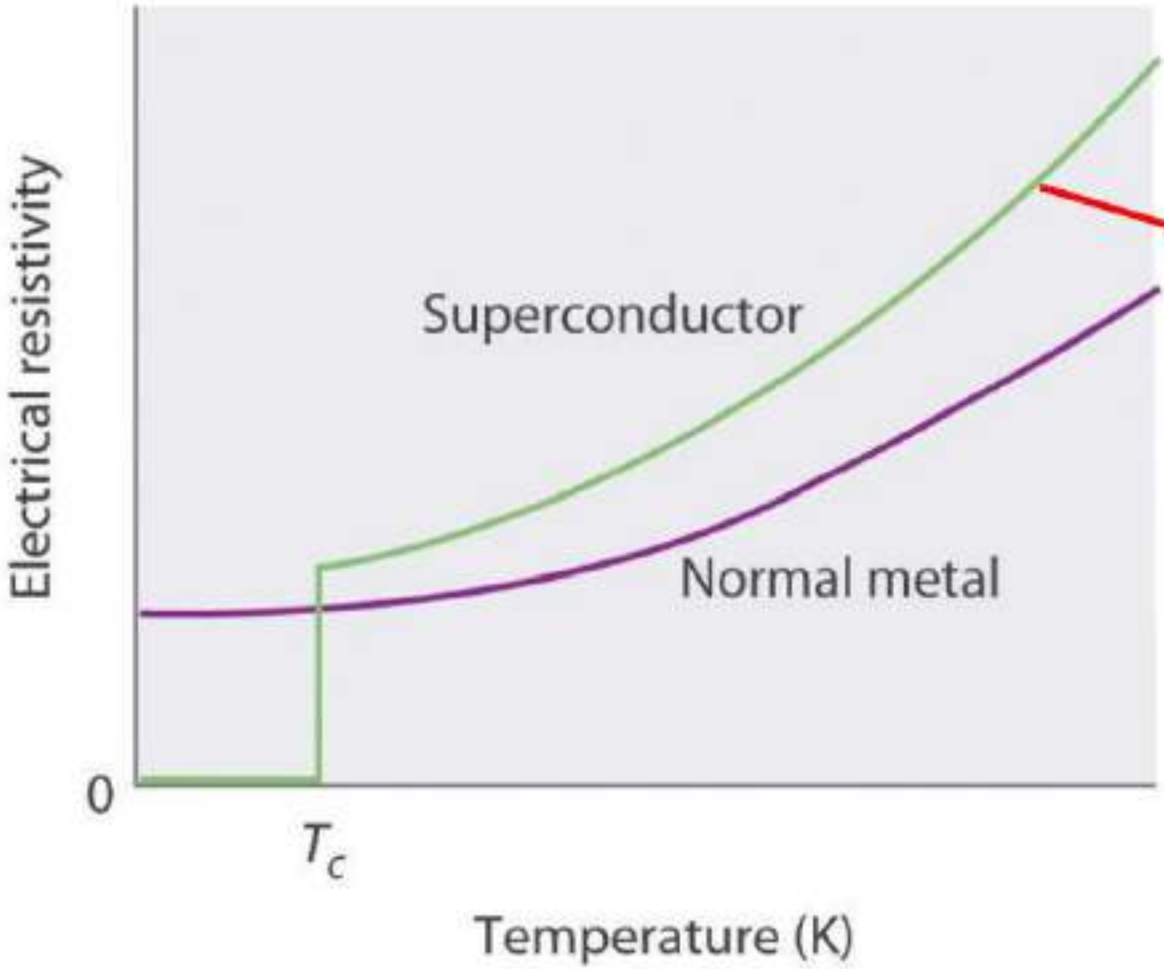
RESISTANCE VERSUS TEMPERATURE



- Generally the electrical resistivity of an ordinary metallic conductor decreases gradually as temperature is lowered

- Even near absolute zero, a real sample of a normal conductor shows some resistance

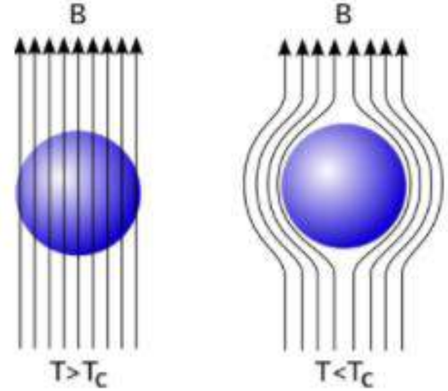
RESISTANCE VERSUS TEMPERATURE



- But in a superconductor, the resistance drops abruptly to zero when the material is cooled below its critical temperature, Tc

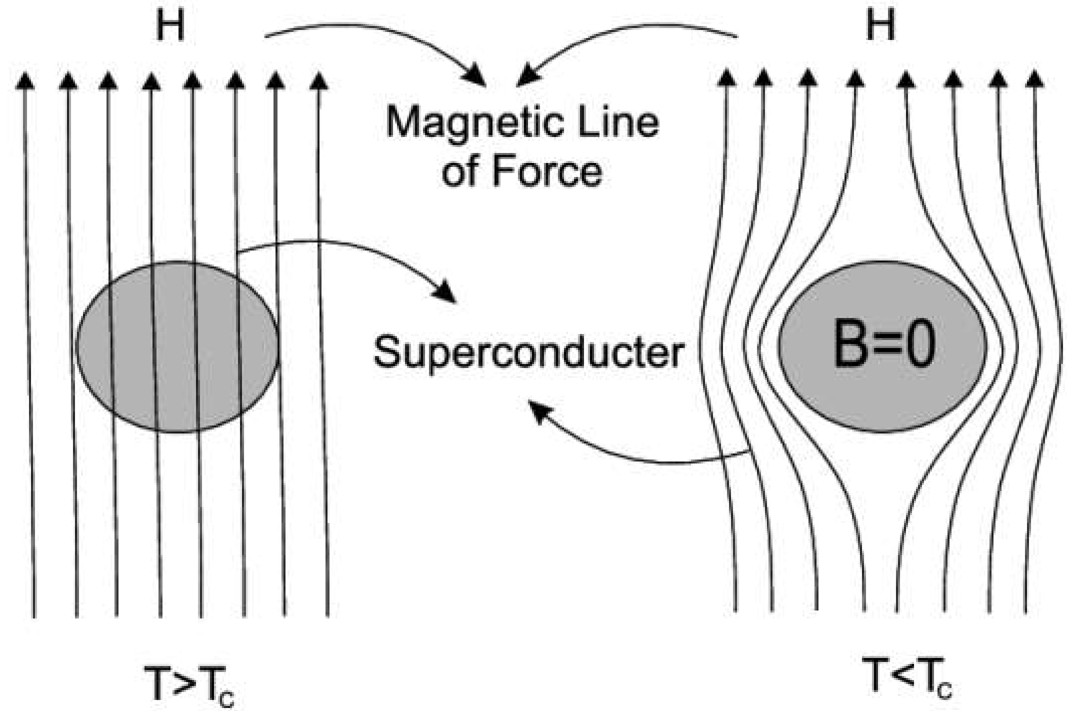
MEISSNER EFFECT

- Superconductors exhibit unique features:
  - →ability to perfectly conduct current.
  - →many expel magnetic fields during the transition to the superconducting state.
- This is due to Meissner effect by which superconducting materials set up electric currents near their surface at T_c →cancelling the fields within the material itself.
- Stationary magnet on superconductor demonstrates this effect:
  - →superconductor cools through its T_c
  - →the expulsion of magnetic flux from the conductor causes the magnet to levitate above the material/ floats above the surface of the superconductor



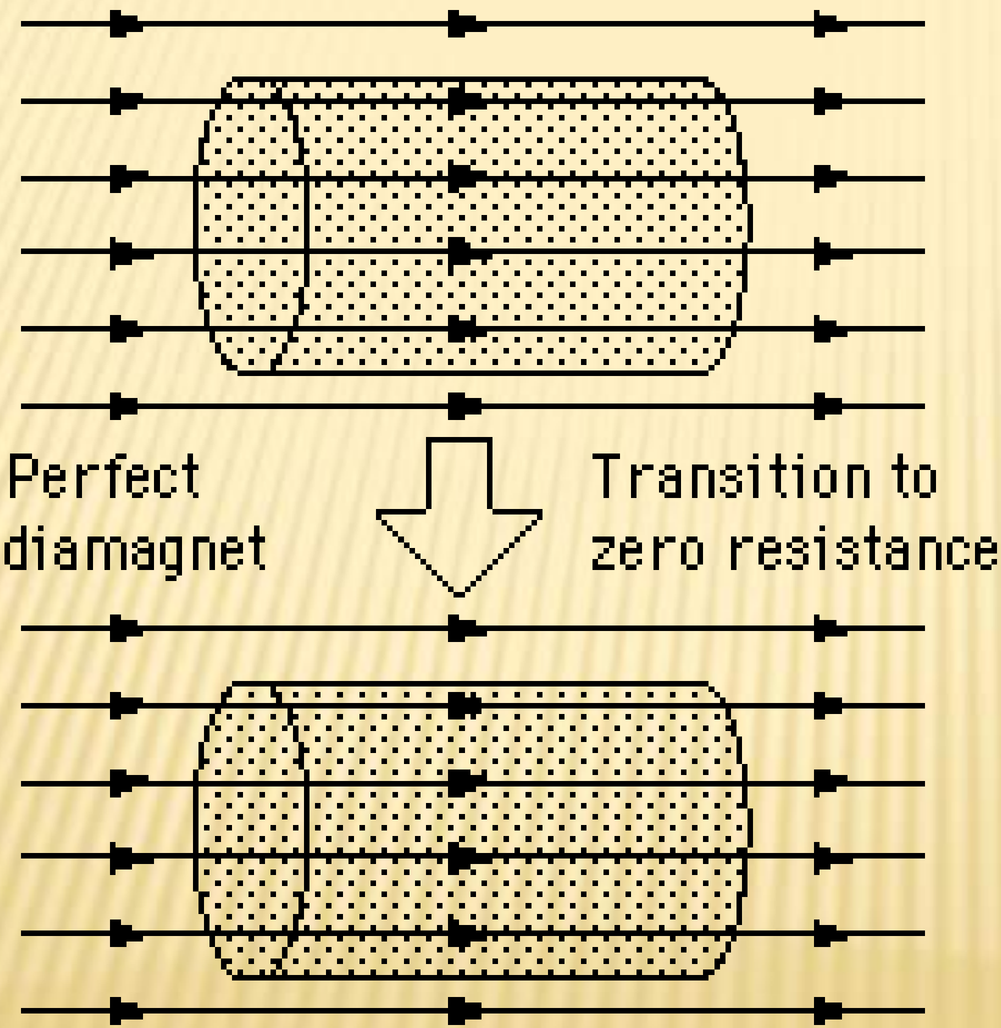
The Meissner effect: a superconductor's magnetic flux above (left) and below critical temperature.

MEISSNER EFFECT



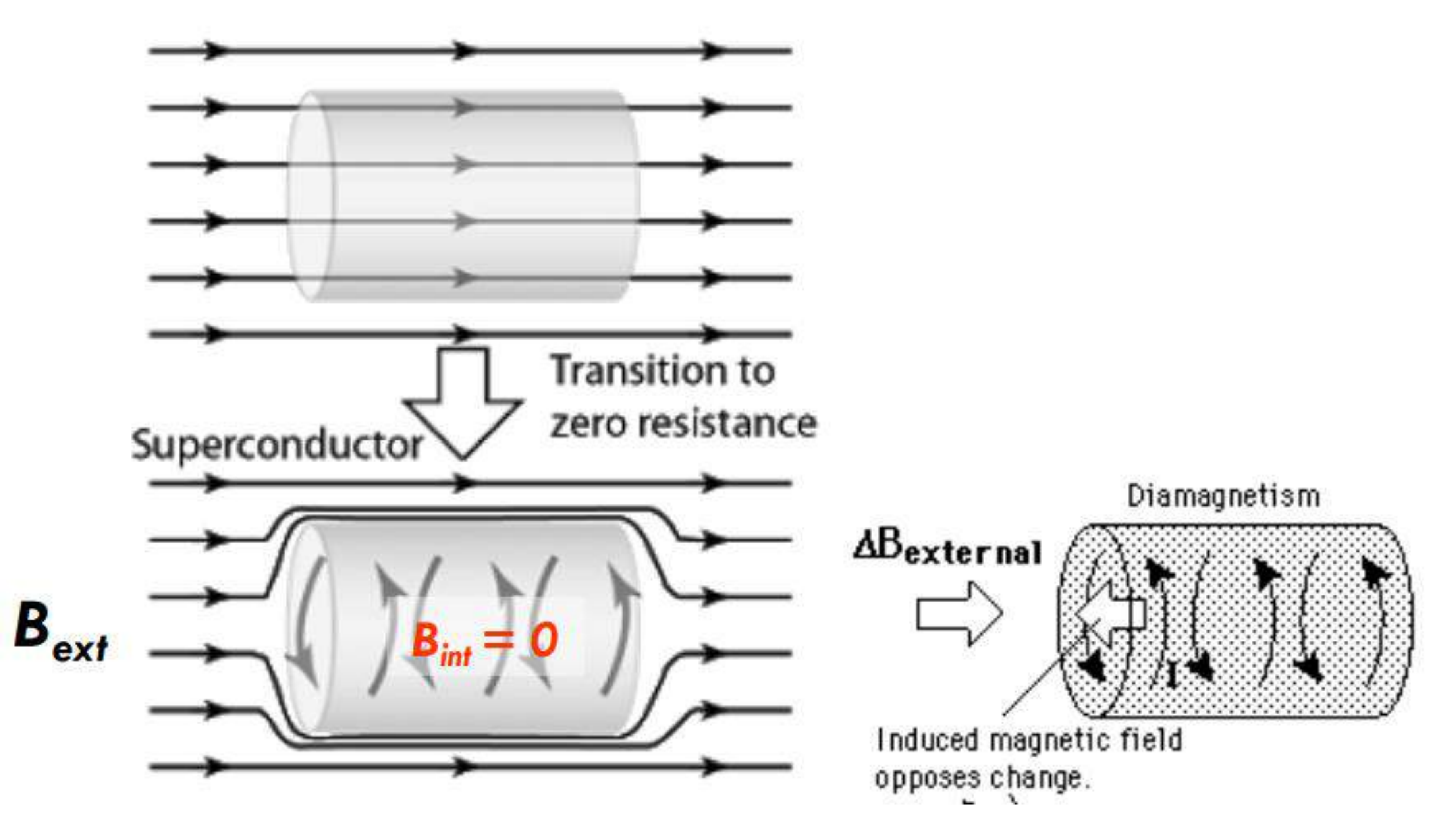
- T>Tc, when a superconducting material is placed in external magnetic field, lines of magnetic induction pass through its body.
- T<Tc, lines of induction are pushed out of the superconductor body.
- This is when the material makes the transition from the normal to superconducting state, it actively excludes magnetic field from its interior.
- Therefore, inside the superconductor **B=0.**

Non-superconductor (Normal Metal)



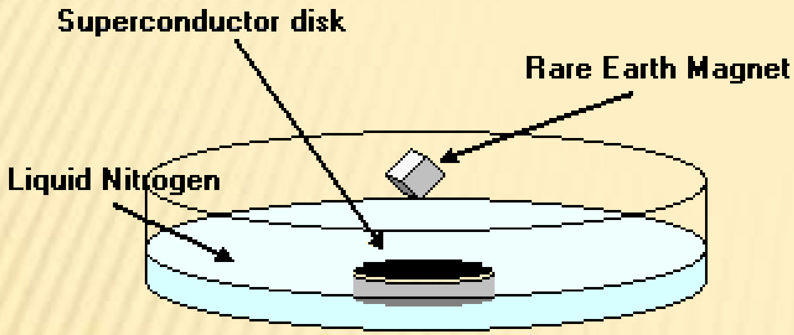
$B_{int} = B_{ext}$

Superconductor



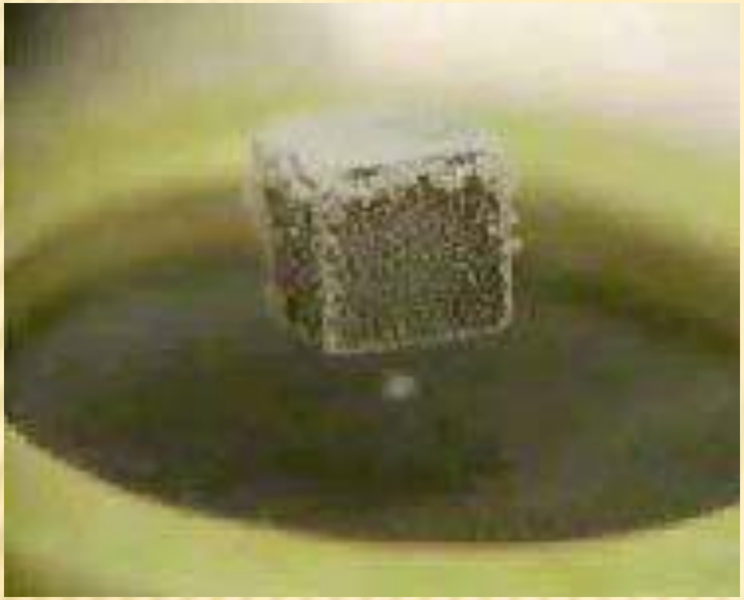
MAGNETIC LEVITATION

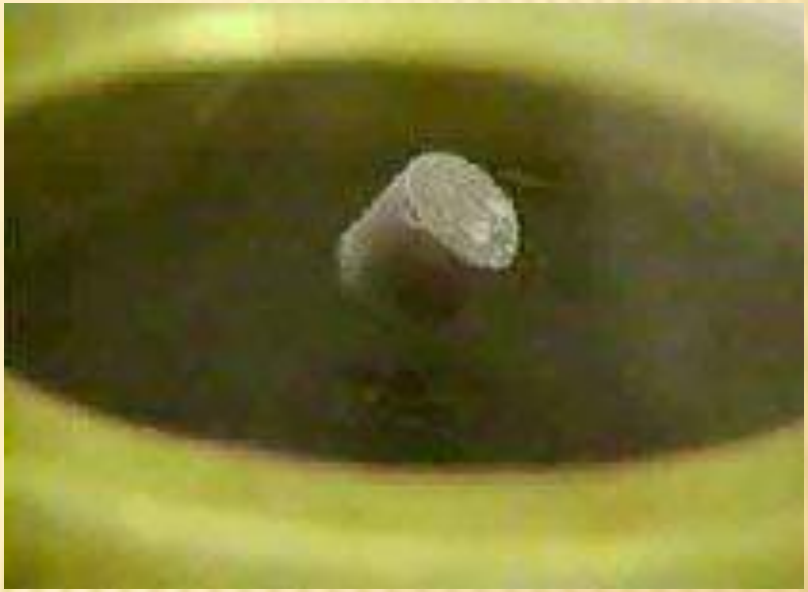
- Magnetic fields are actively excluded from superconductors (Meissner effect).
- If a small magnet is brought near a superconductor, it will be repelled because induced supercurrents will produce mirror images of each pole.
- If a small permanent magnet is placed above a superconductor, it can be levitated by this repulsive force.



The Meissner Effect

A magnet is hovering over a superconductor cooled by liquid nitrogen, demonstrating that magnetic fields cannot penetrate the superconductor





Magnetic Levitation

TYPES I SUPERCONDUCTOR

There are 30 pure metals which exhibit zero resistivity at low temperature.

They are called Type I superconductors (*Soft Superconductors*).

The superconductivity exists only below their critical temperature and below a critical magnetic field strength.

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

TYPES II SUPERCONDUCTOR

Starting in 1930 with lead-bismuth alloys, were found which exhibited superconductivity; they are called Type II superconductors (*Hard Superconductors*).

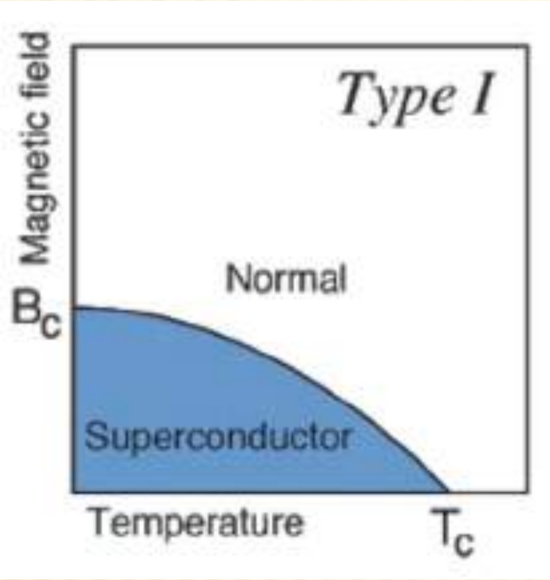
They were found to have much higher critical fields and therefore could carry much higher current densities while remaining in the superconducting state.

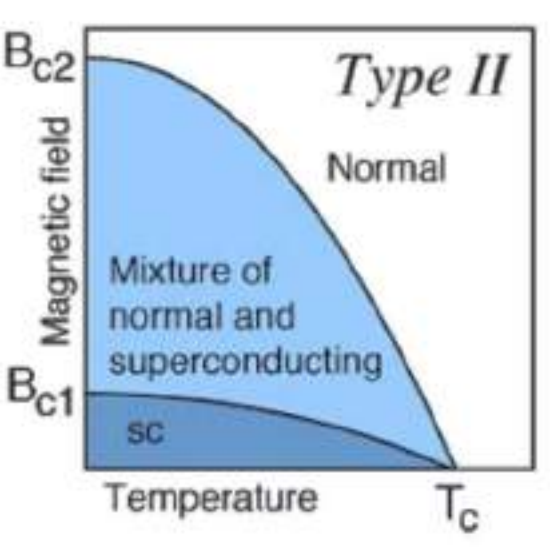
Type II Superconductors

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

THE CRITICAL FIELD





An important characteristic of all superconductors is that the superconductivity is "quenched" when the material is exposed to a sufficiently high magnetic field.

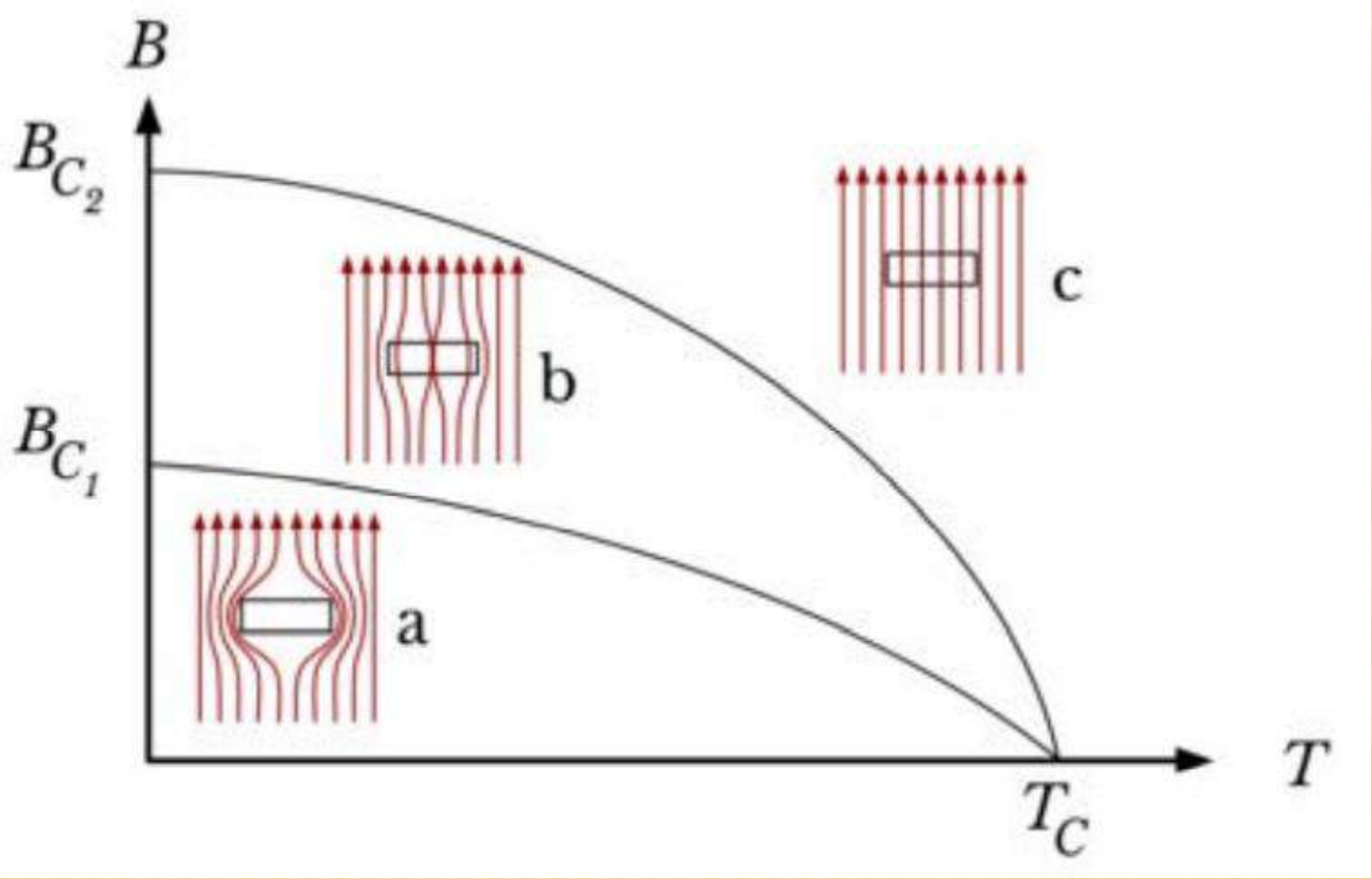
This magnetic field, B_c, is called the critical field.

Type II superconductors have two critical fields.

The first is a low-intensity field, B_{c1}, which partially suppresses the superconductivity.

The second is a much higher critical field, B_{c2}, which totally quenches the superconductivity.

THE CRITICAL FIELD: TYPE II



THE CRITICAL FIELD

The critical field, B_c, that destroys the superconducting effect obeys a parabolic law of the form:

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

where B_o = constant, T = temperature, T_c = critical temperature.

In general, the higher T_c, the higher B_c.

EXAMPLE QUESTION

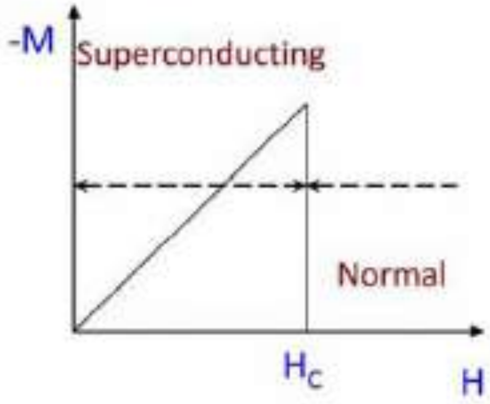
- The transition temperature for Pb is 7.2K. However at 5K it loses the superconducting property if subjected to a magnetic field of 3.3×104 A/M. Find the maxiumum value of H which will allow the metal to retain its superconductivity at 0K.

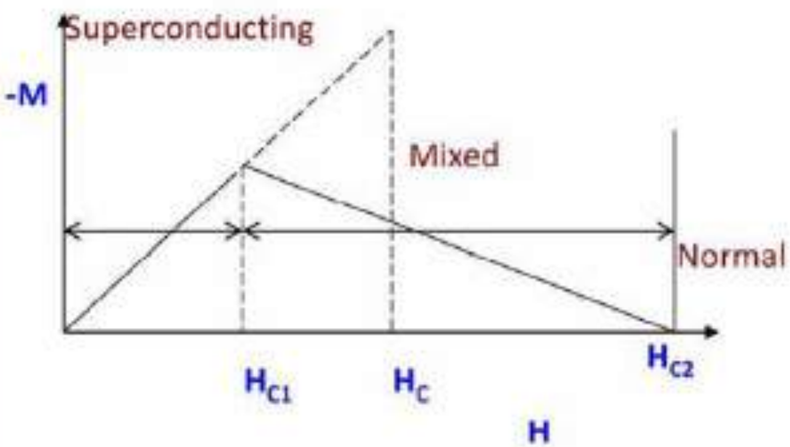
COMPARISON OF TYPE I & II

Type I - they have a single critical field, above which all superconductivity is lost.

Type II - they have two critical fields, between which they allow partial penetration of the magnetic field.

TYPE I	TYPE II
• Sudden loss of magnetization	• Gradual loss of magnetization
• Exhibit Meissner Effect	• Does not exhibit complete Meissner Effect
• One H_C = 0.1 tesla	• Two H_Cs – H_{C1} & H_{C2} (≈30 tesla)
• No mixed state	• Mixed state present
• Soft superconductor	• Hard superconductor
• Eg.s – Pb, Sn, Hg	• Eg.s – Nb-Sn, Nb-Ti





SUPERCONDUCTOR CERAMICS

The ceramic materials used to make superconductors are a class of materials called perovskites.

One of these superconductor is an yttrium (Y), barium (Ba) and copper (Cu) composition.

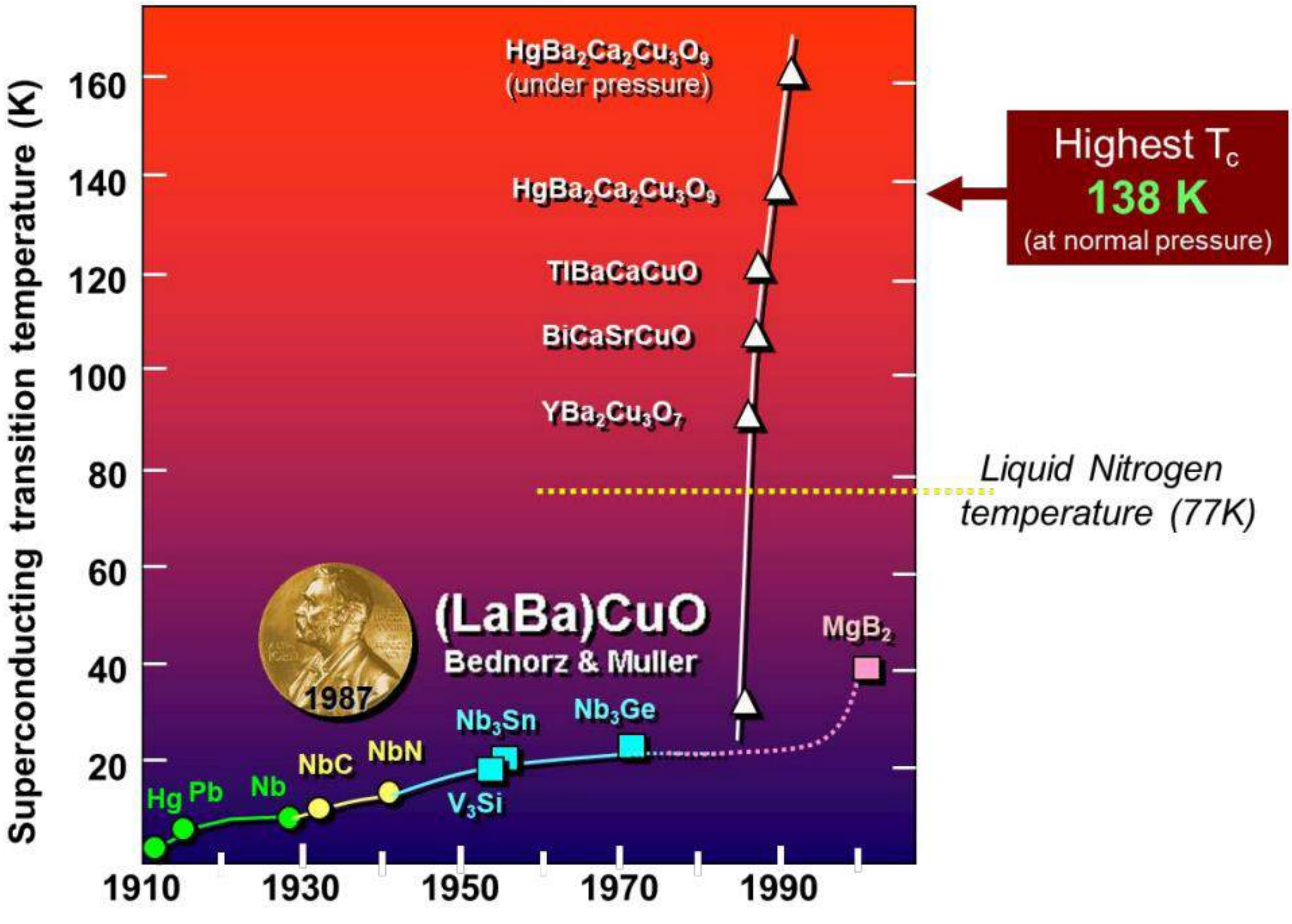
Chemical formula is $YBa_2Cu_3O_7$.

This superconductor has a critical transition temperature around 90K, well above liquid nitrogen's 77K temperature.

HIGH TEMPERATURE SUPERCONDUCTOR (HTS) CERAMICS

HTS materials the most popular is orthorhombic $YBa_2Cu_3O_{7-x}$ (YBCO) ceramics.

Nonoxide/intermetallic solid powders including MgB_2 or $CaCuO_2$ or other ceramics while these ceramics still have significant disadvantages as compared to YBCO raw material.

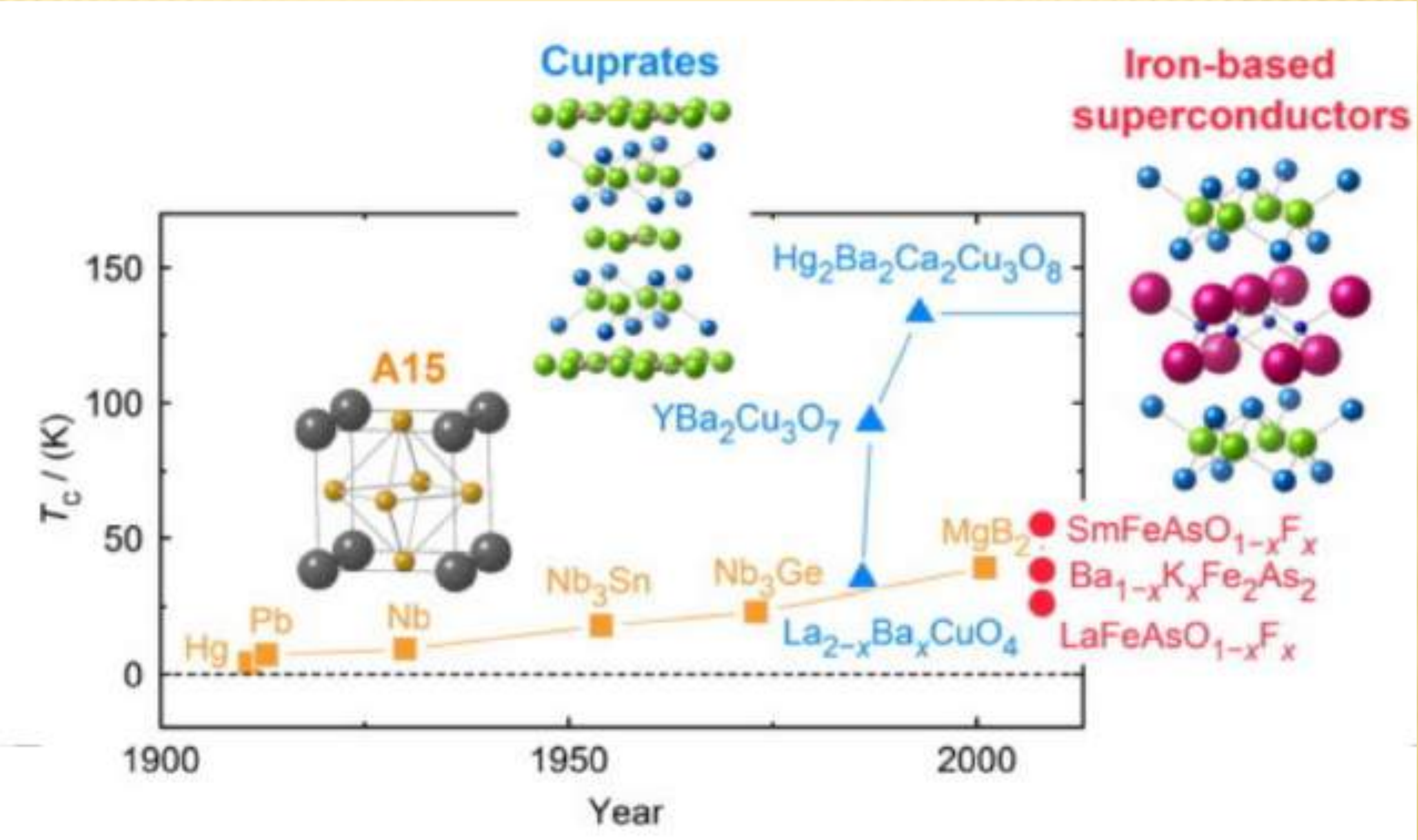


Superconductivity in alloys and oxides

CRITICAL TEMPERATURES, TC IN INORGANIC SUPERCONDUCTORS

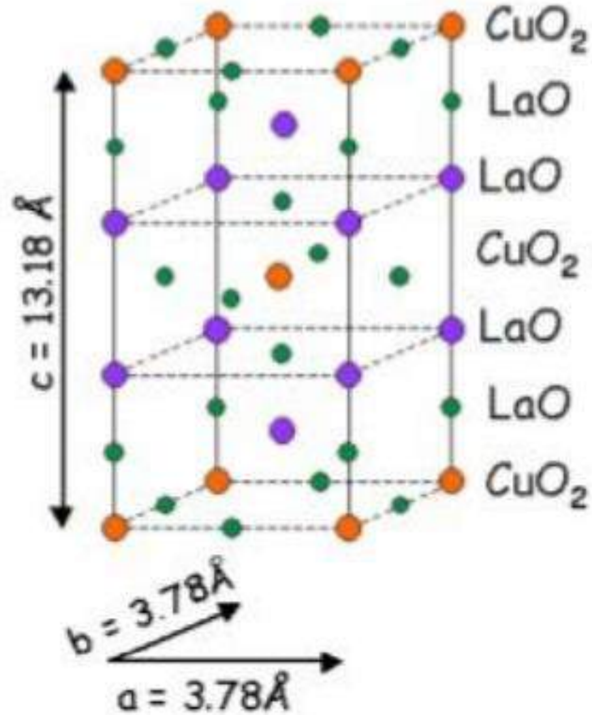
Compound	T_c (K)
$PbMo_6S_8$	12.6
$SnSe_2(Co(C_5H_5)_2)_{0.33}$	6.1
K_3C_{60}	19.3
Cs_3C_{60}	40 (15 kbar applied pressure)
$Ba_{0.6}K_{0.4}BiO_3$	30
$La_{1.85}Sr_{0.15}CuO_4$	40
$Nd_{1.85}Ce_{0.15}CuO_4$	22
$YBa_2Cu_3O_7$	90
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125
$HgBa_2Ca_2Cu_3O_{8+d}$	133

HTS CERAMICS



COPPER OXIDE BASED HTS CERAMICS

- Cuprate superconductors are generally considered to be two-dimensional materials with their superconducting properties determined by electrons moving within weakly coupled copper-oxide (CuO_2) layers. Neighboring layers containing ions such as lanthanum, barium, strontium, or other atoms act to stabilize the structure and dope electrons or holes onto the copper-oxide layers.



- Cuprates Superconducting materials.

  $HgBa_2Ca_2Cu_3O_x$ (critical temperature to 133 K)

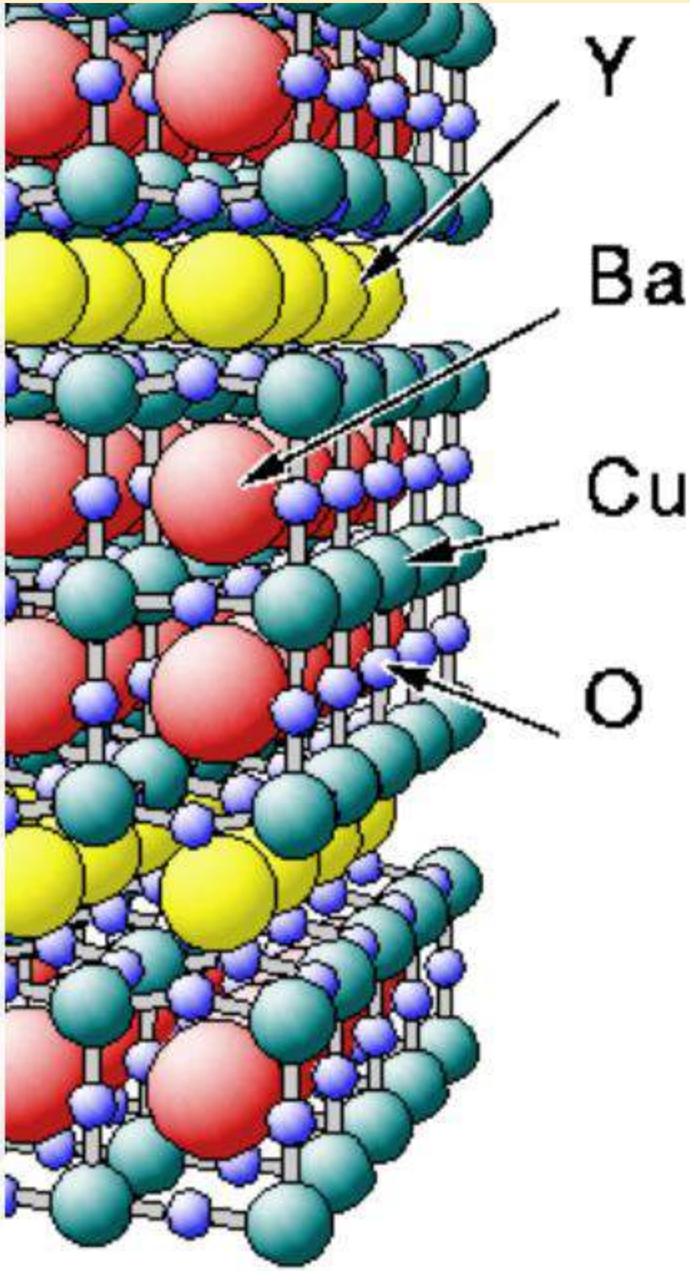
  $Bi_2Sr_2Ca_2Cu_3O_{10}$(BSCCO) (critical temperature to 110 K)

  $YBa_2Cu_3O_7$ (YBCO) (critical temperature to 92 K.)

COPPER OXIDE HTS CERAMICS

- Right side is the structure for **a high temperature superconductor, $YBa_2Cu_3O_7$.**
- This one was the first discovered to have a Tc above the boiling point of liquid nitrogen.
- This is a cuprate and scientists believe only the copper oxide layer is superconducting, but there is much debate and research going on.
- It can be abbreviated YBaCuO.

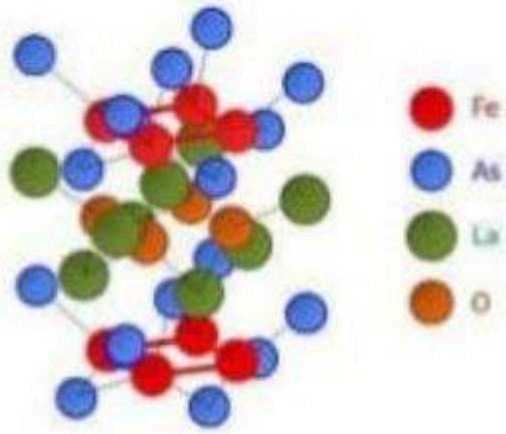
"The electronic states near the Fermi level of high-temperature superconductors derive from the hybridized *d*- and *p* -orbitals of copper and oxygen ions in a square-planar network." *(V.Hinkov et. al)*



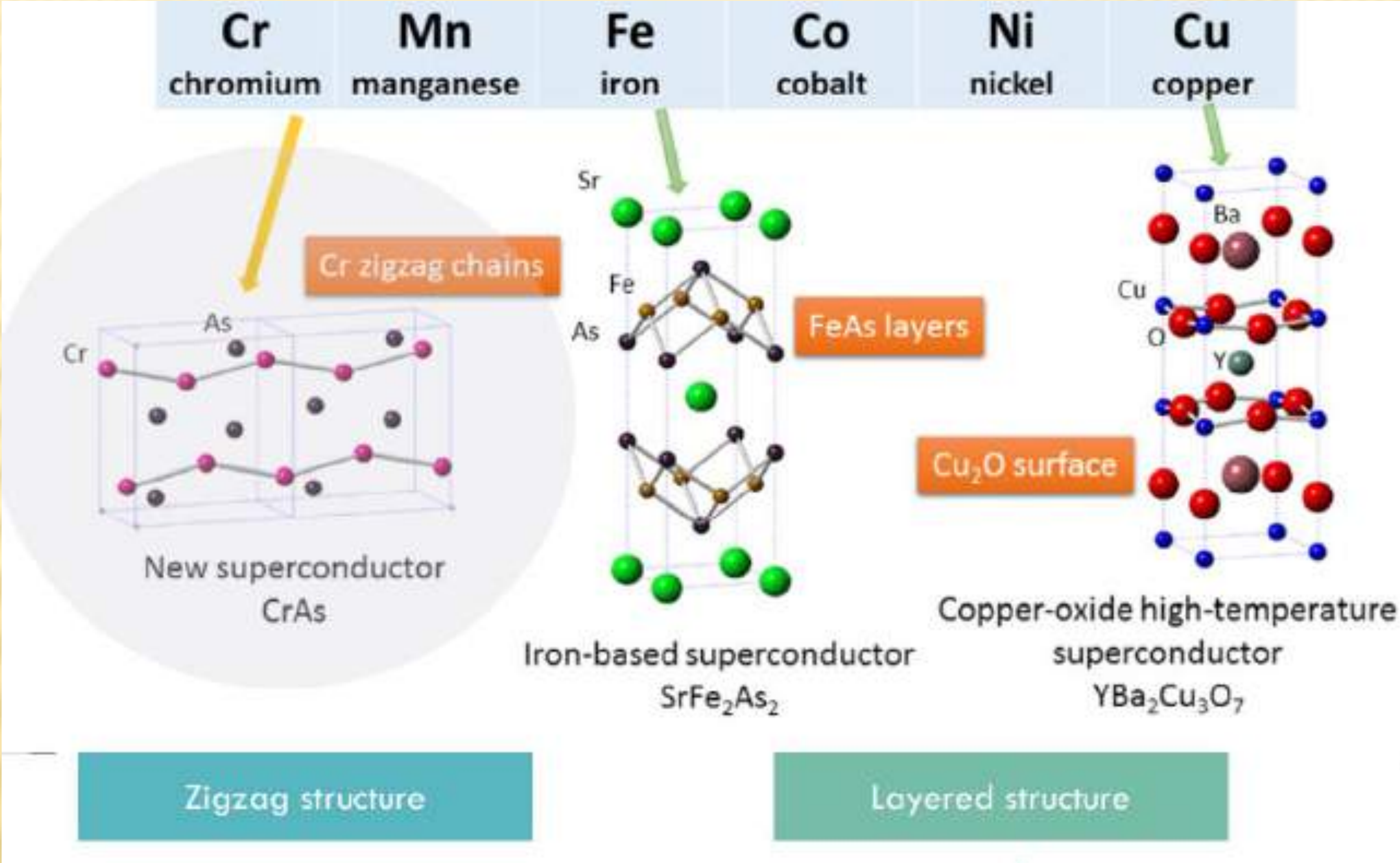
IRON BASED HTS CERAMICS

- Iron-based superconductors contain layers of iron and a pnictide such as arsenic or phosphorus .This is currently the family with the second highest critical temperature, behind the cuprates.

- The crystalline material, known chemically as LaOFeAs, stacks iron and arsenic layers, where the electrons flow, between planes of lanthanum and oxygen.



Crystal structure of LaFeAsO, one of the ferropnictide compounds



**NEW CHROMIUM BASED SUPERCONDUCTORS

- The zigzag structure of CrAs could be influencing the electrons
- This property is rarely reported for superconductive materials

PRODUCT FORM FACTORS

- Suppliers of superconductors and superconducting materials offer products in various different forms
- **Raw superconducting materials**
  - include chemical compounds in the form of powders or crystals.
  - Superconducting powder is incorporated into the manufacture of more efficient fuel cells, gas separation membranes, and lithium-ion batteries.
- **Magnets**
  - are produced for MAGLEV and MRI applications, as discussed below, as well as microscopy and NMR/EPR spectroscopy.
- **Wire and cable**
  - are used in superconductive power transmission and scientific research in ultra-high magnetic fields.
- Superconductor manufacturers may specialize in the advancement of a certain superconducting compound→niobium-based formulas or magnesium diboride (MgB_2).

APPLICATIONS

- Superconductors are not available on a wide commercial scale due to the extensive cooling necessary to reach superconductive states.
- They are common in a few specialized applications, including:
- **MAGLEV trains**
  - use superconductive magnets to practically eliminate friction between the train and the tracks.
  - The use of conventional electromagnets would waste vast quantities of energy via heat loss and necessitate the use of an unwieldy magnet, whereas superconductors result in superior efficiency and smaller magnets.
- **Magnetic resonance imaging (MRI)**
  - uses superconductor-generated magnetic fields to interact with hydrogen atoms and fat molecules within the human body.
  - These atoms and molecules then release energy that is detected and formed into a graphic image.
  - MRI is a widely used radiographic method for medical diagnosis or staging of diseases such as cancer.
- **Electric generators**
  - built with superconductive wire have achieved 99% efficiency ratings in experimental tests but have yet to be built commercially.
- **Electric power generation**
  - using superconductive cables and transformers has been experimentally tested and demonstrated.

MAGLEV TRAINS

Miyazaki Maglev (Japan) Test Track, 40 km

603 km/h

- No friction
- Super-high speed
- Safety
- Noiseless