High Temperature Superconductivity

A Journey from Discovery to Promising Horizons

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Superconductivity: A brief Overview

Heike Kamerlingh Onnes, the first person to liquefy Helium, the feat which enabled him to achieve temperatures close to Absolute Zero (0K or -273.15C), and little did he know, this discovery was going to change the future of material sciences**.** With the ability to attain temperatures as low as 4.2K, Onnes studied the behavior of metals at this temperature and noticed that Mercury's resistance decreased as the temperature fell, and at 4.2K, resistance was close to a millionth of an **Ohm (Ω)** – this was the **First Instance of Superconductivity.** (Figure 1 shows this trend as the resistance falls to zero at the critical temperature)

What is Superconductivity? Assume a circuit connected to the power supply. In a metallic conductor, **electrons experience resistance** as they get knocked off-course when they move along the wire; upon switching off the power supply, electrons slow down and directions - null average flow of charge**.** However, in a superconduc **even when the the power supply is off and** experience **zero resistance in their path** – ***Perfectly Frictionless Electricity.***

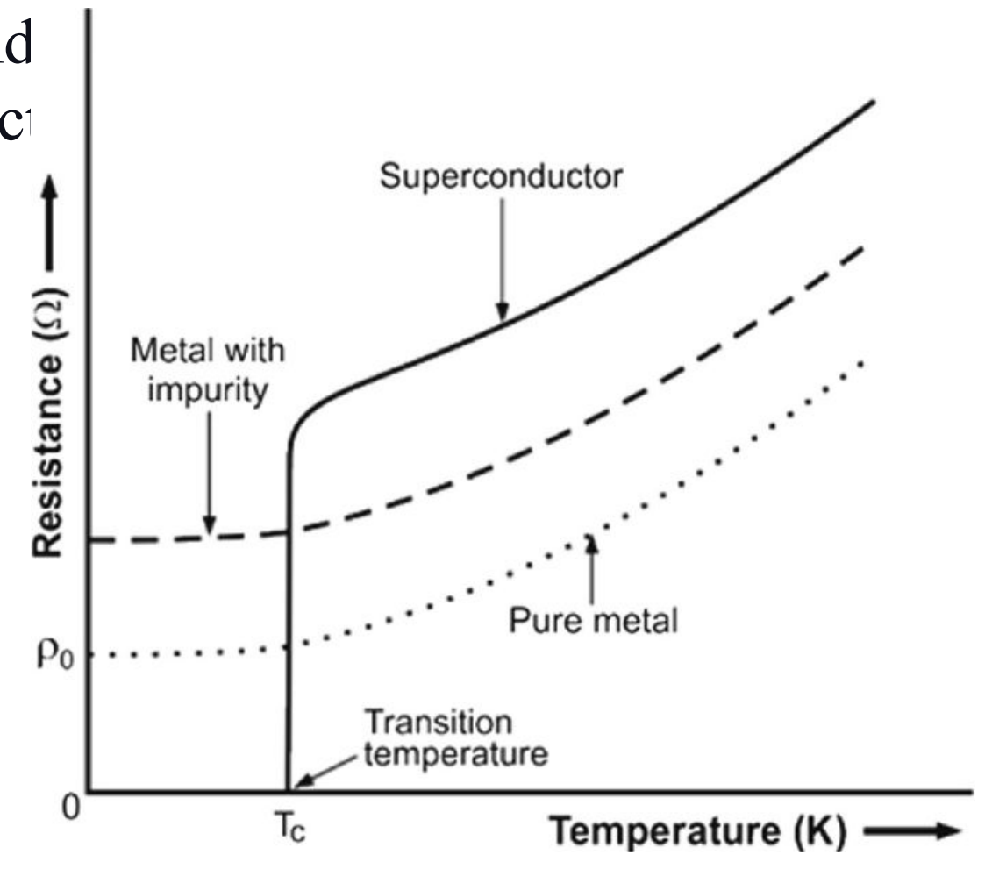

Figure 1. Resistance– Temperature Graph of Superconductors, Impure and Pure Metals [3]

Superconductors exhibit superconductivity under certain conditions.

1.The conductor must reach a certain ***Superconducting Transition Temperature OR Critical Temperature (T_C)*** to show superconductivity**. *(Figure 1)***

2. The magnetic field applied should be below the maximum magnetic field value – the *Critical* ***Field (B_C).***

3. The current per unit area through the superconductor must be below the ***Critical Current Density*** ***(J_C),*** the maximum current that can pass through a given cross-sectional area of the material.

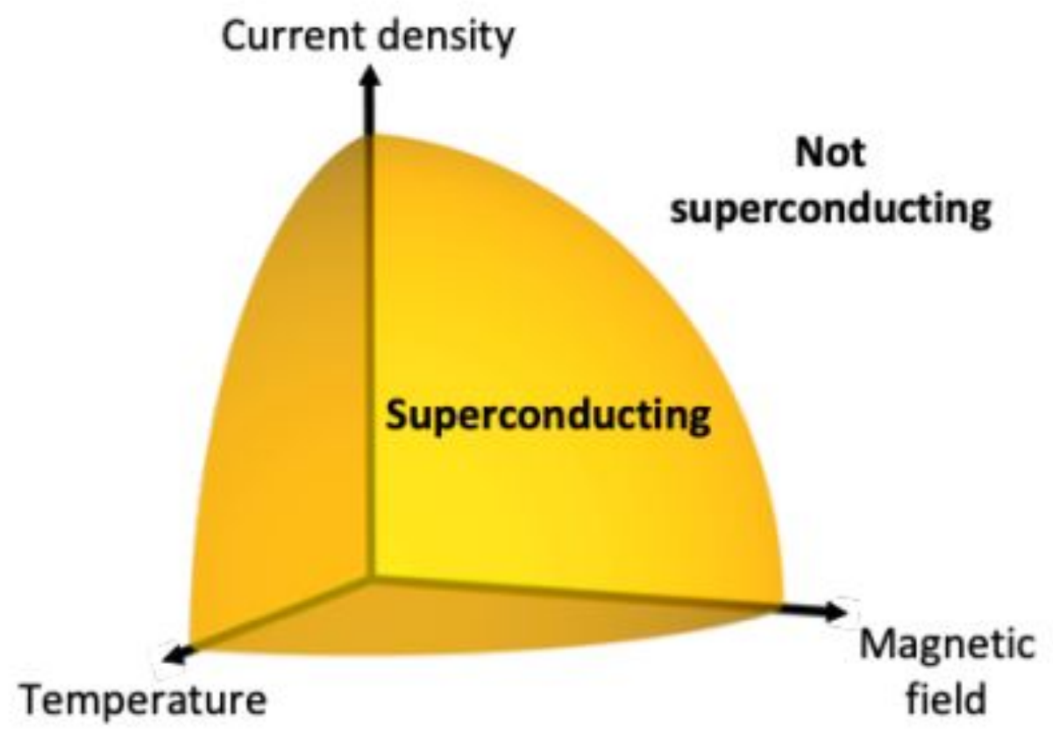

Figure 2. Critical Surface.[1]

However, all Critical Parameters influence each other, this creates a problem in maintaining these parameters. For instance, if the superconductor cools below $\mathbf{T_C}$, the magnetic field and the current density will increase and may exceed $\mathbf{B_C}$ **or** $\mathbf{J_C}$. The same problems occur while varying the current density, $\mathbf{J_C}$, and magnetic field $\mathbf{B_C}$. To solve this interdependency problem, the parameters are visualized on a 3D graph of Temperature, Magnetic Field and, Current Density, called ***Critical Surface*** and the material exhibits superconductivity at any point under the Critical Surface (Blue area in Figure 3)

The Meissner Effect

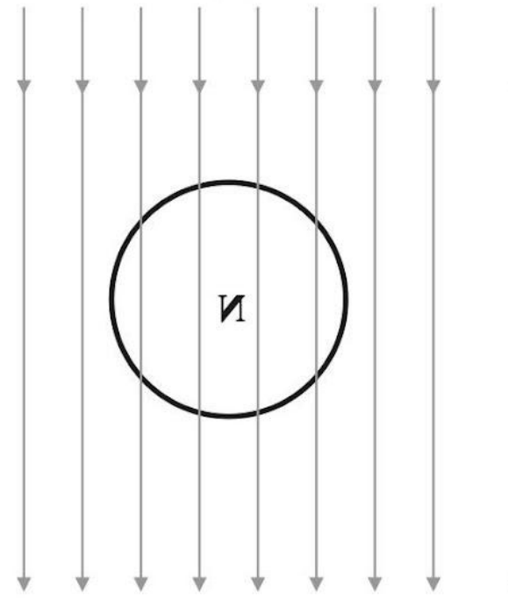

Figure 3a. Field lines when **T > $\mathbf{T_C}$** [3]

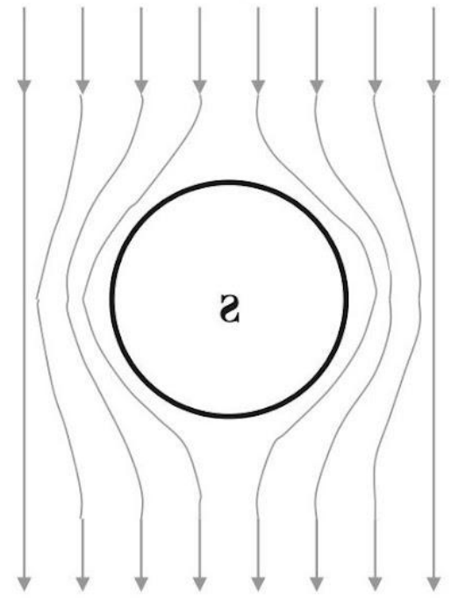

Figure 3b. Field lines when **T < $\mathbf{T_C}$** [3]

A spherical superconductor is kept inside **an external Magnetic field(H)** at a temperature above $\mathbf{T_C}$ so the material acts as a metallic conductor. While the **temperature(T) > $\mathbf{T_C}$**, the magnetic field lines will pass through the material, as shown in Figure 3a. If **T** increases to a value greater than $\mathbf{T_C}$**, the material is a superconductor** and the magnetic field lines will pass around the superconductor, leaving no magnetic interaction within the material itself (Figure 3b) and the superconductor will levitate mid-air, as shown in Figure 4.

The reason behind the levitation is that the superconductor acts as a **diamagnet**, which means it has a **Magnetization (M),** which has a direction opposite to **H (shown in Figure 6),** thus cancelling each other out, this means that no magnetism is induced inside the superconductor as the field lines of **H** pass around the material.

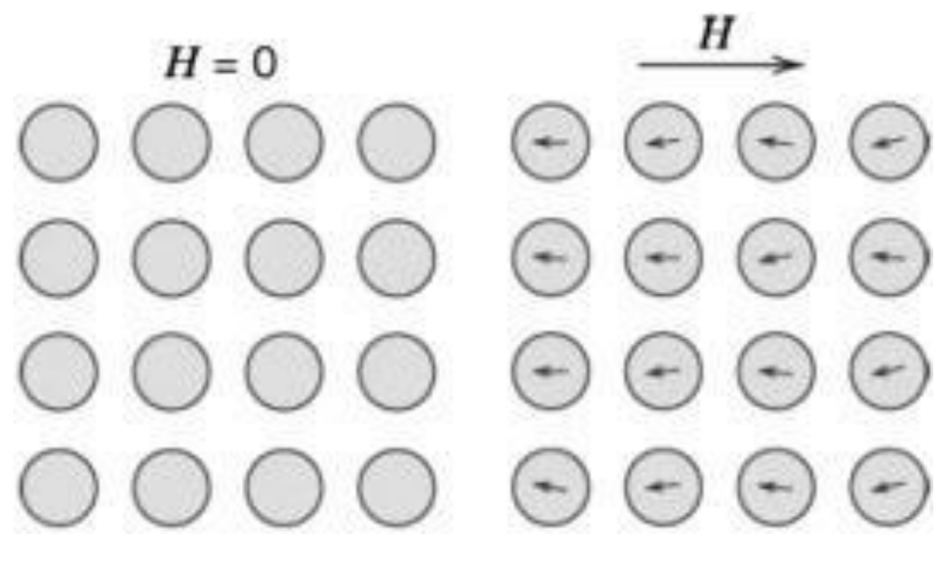

Figure 5. Diamagnet with M in the opposite direction as compared to H [10]

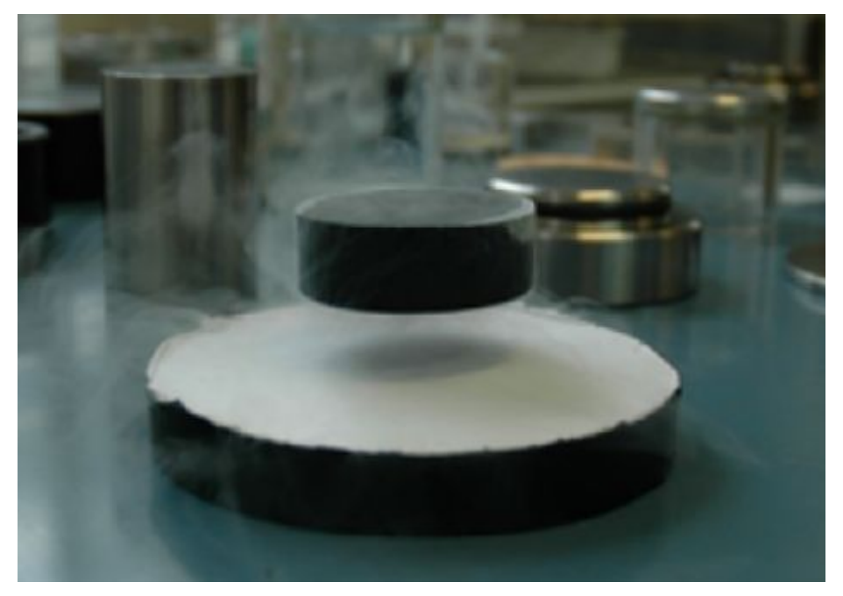

Figure 4. The Meissner Effect [1]

The Meissner Effect is also used to separate superconductive material. Superconductive materials are divided based on their interaction in a Magnetic Field, also briefly on whether or not they showcase the Meissner Effect.

Type I vs Type II Superconductors

Type I Superconductor	**Type II Superconductor**
A type I superconductor, when placed in a magnetic field of strength H, perfectly obeys Meissner's Effect. This type of superconductivity is typically found in Pure Metals.	Assume a type II superconductor as a cylinder and a **magnetic field of strength H** passes through the cylinder. **When H < $\mathbf{H_{C1}}$** (the lower critical field), the cylinder behaves like a superconductor and Meissner's effect is observed
The diagram below **plots –M with H**, which shows when the **external Magnetic Field (H) > Critical Field ($\mathbf{H_C}$),** the material acts as a conductor. **When H < $\mathbf{H_C}$**, the material remains as a superconductor	As **H increases** further but stays **below $\mathbf{H_{C2}}$** (the upper critical field), parts of the cylinder experience superconductivity due to partial magnetic induction inside the material – this is called the **MIXED STATE REGION. Finally, when H > $\mathbf{H_{C2}}$, the material is a normal conductor**

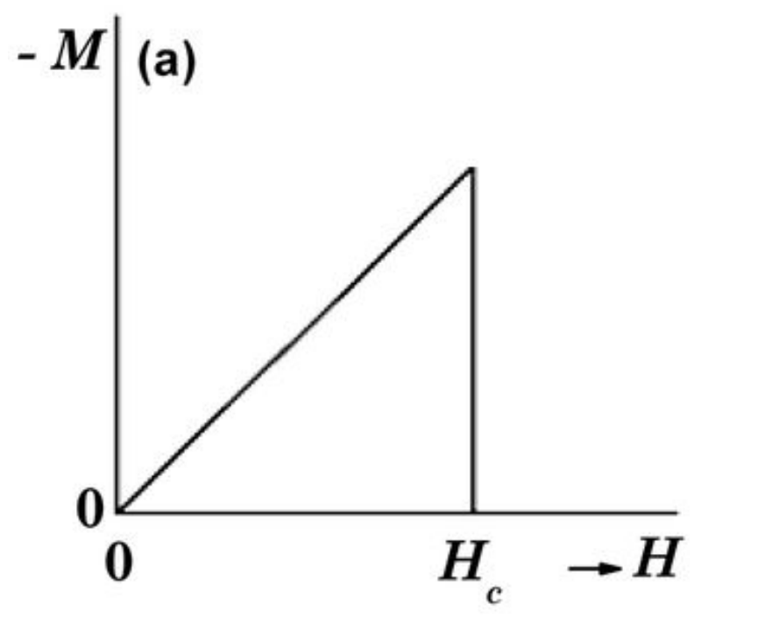

Figure 6. Negative Magnetization (M) – External Magnetic Field(H) Graph for Type I S.C. [6]

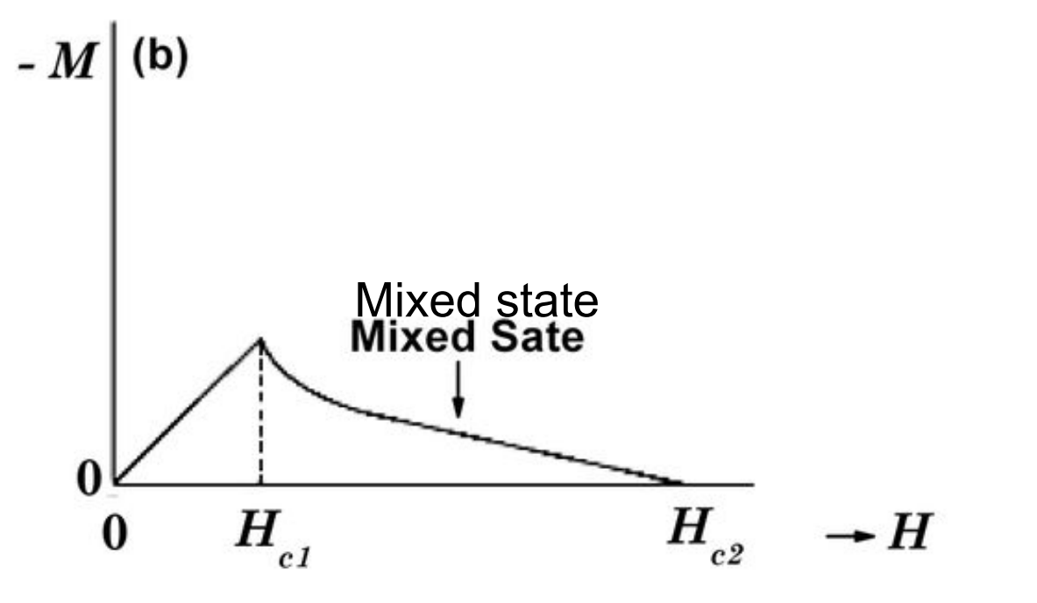

Figure 7. Negative Magnetization (M) – External Magnetic Field(H) Graph for Type II S.C. [6]

High Temperature Superconductivity

The discovery of **Cuprates(anionic copper complexes)** in superconductivity was a new era for this branch of Physics. Within a few months of discovering Cuprates in superconductivity, the **Critical Temperature ($\mathbf{T_C}$) had reached temperatures exceeding liquid nitrogen values (about 60-75K).** The idea behind achieving superconductivity at such high temperatures revolved around electron-lattice interaction. **Superconductivity in Cuprates is observed in $\mathbf{CuO_2}$ layers (see Figure 8)**, while the insulating layers serve as 'charge suppliers' for the superconducting layer.

The simplest Copper Oxide perovskites are insulators. For the perovskites to become superconducting alloys, the crystals require doping. **Doping increases the number of charge carriers in the Fermi Level**. Copper Oxide Perovskites can have two forms of doping. First, to **substitute metal atoms in the Intermediate planes by higher valency atoms** and second, to **change the number of Oxygen atoms.**

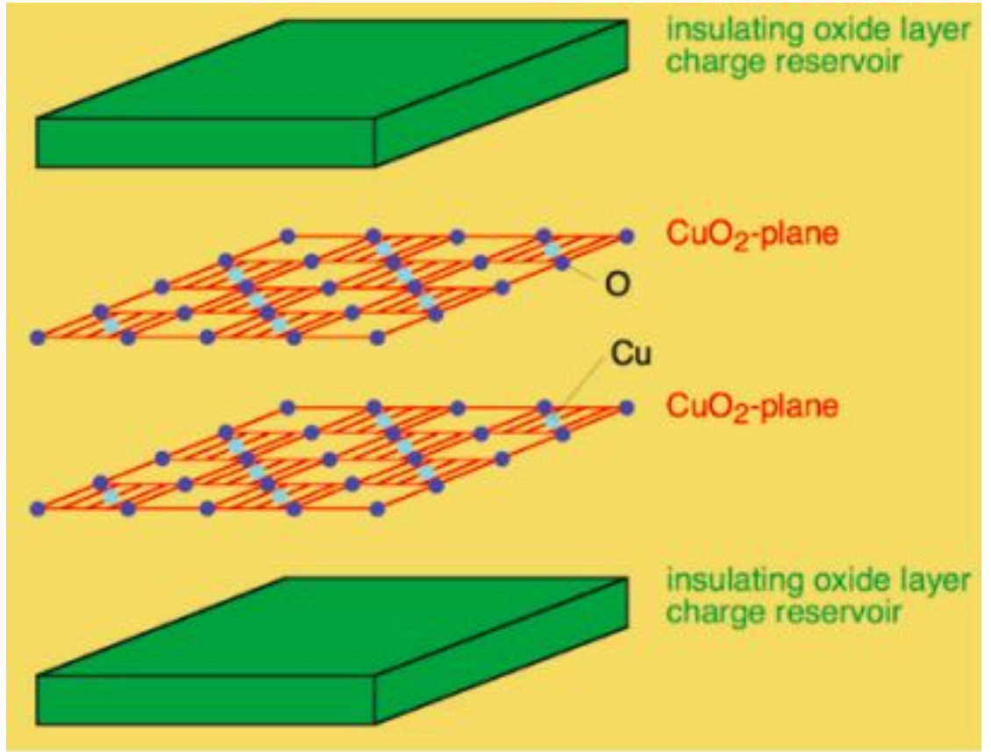

Figure 8. Schematic of a Cuprate HTS

Room Temperature Superconductivity

Room Temperature Superconductivity is a feat that everyone associated with superconductivity is trying to achieve; however, all advancements in Room Temperature Superconductivity in the past have been under unimaginable, impossible conditions.

It's rumored that **Lanthanum hydride's (see Figure 9) $\mathbf{T_C}$ approaching Room temperature but at a pressure of hundreds of Gigapascals. Similarly, Calcium Hydride and Yttrium Hydride may also conduct at/near room temperature at around 350GPa**, which is impossible to apply in the present world of physics.

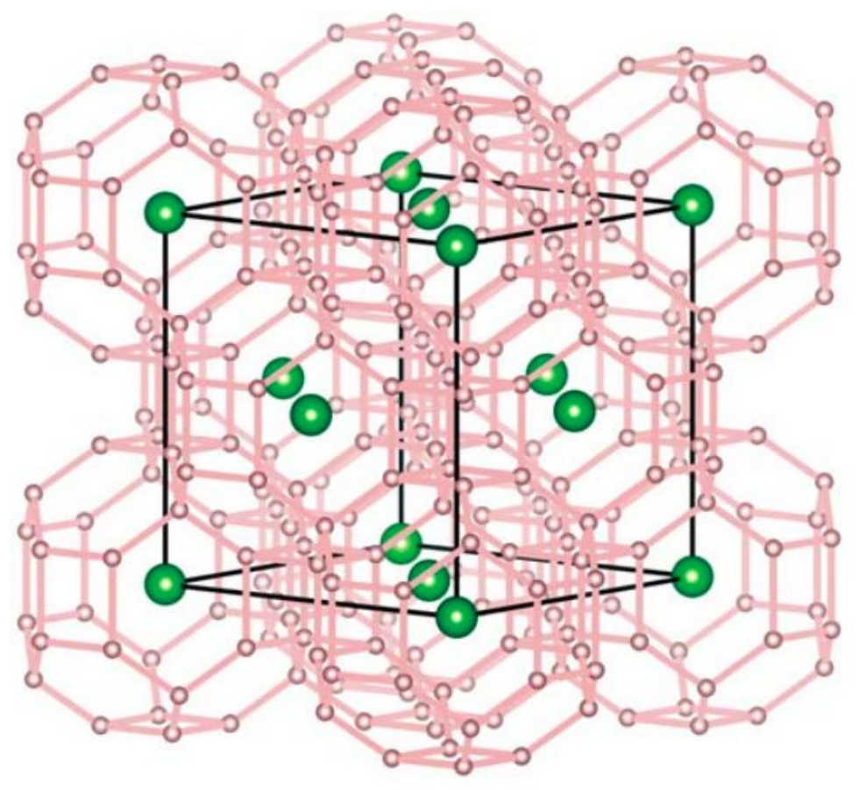

Figure 9: Superconductive structure of Lanthanum Hydride [8]

Under intense pressure, $\mathbf{H_2}$ becomes semi-metallic with the low-density presence of both holes and electrons. Increasing pressure further increases the Overlap between the valence and conduction bands; thus, hydrogen gains metallic properties. Moreover, with a sufficient density of states N(0), hydrogen becomes a superconductor. Such theoretical experiments related to superconductivity suggest that **in molecular hydrogen, $\mathbf{T_C}$ is approaching room temperature**, whereas, **in atomic hydrogen, the $\mathbf{T_C}$ is above room temperature** – this claims the presence of Room Temperature Superconductivity.

Future Applications of HTC

The Future of Particle Accelerator

The physics community has been exploring various applications of High-temperature Superconductivity like SMES, magnetic flywheel, and energy storage. However, the recent use of HTS lies in the **Large Hadron Collider (LHC) at CERN's 27km Long 'atom smashing machine**' sets up the future for HTS. The **LHC consists of two proton (hadron) beams** that accelerate to **energies close to 6.5TeV: $\mathbf{10^{12}}$ times as much as a single eV**. The proton beams are then collided head-on to detect smaller particles. What steers the proton beams? **HIGH TEMPERATURE SUPERCONDUCTORS lead the hadron beams across the tunnel**. The same method was used to detect the Higgs Boson for the first time in 2012. The next planned project to take over from the LHC is the ***Future Circular Collider (FCC),*** a planned research infrastructure that can **generate up to 100TeV of energy - 8 times more than the LHC. Using HTCs operating at 20T, the size of the FCC is also reduced by a 20km circumference.**

Nuclear Fusion Power Plants

Nuclear Fusion is the process in which **light atomic nuclei combine to create larger nuclei** and release immense amounts of energy. So, to achieve this on Earth, Temperatures 150 million ºC hotter than the Sun are required. Theoretically, it is impossible to replicate nuclear fusion on Earth – but so was high-temperature superconductors; a century ago. Nuclear Reactors require a lot of space. Therefore, the **design for the reactor is compressed using HTS magnetic coils which generate a high magnetic field.**

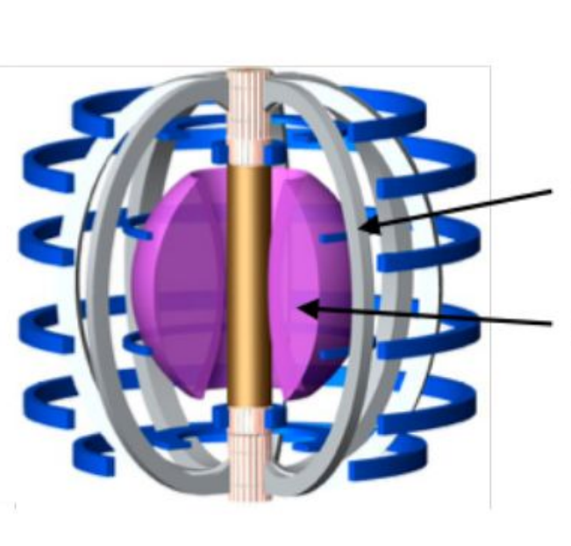

Figure 10. Compact Nuclear Fusion Design [1]

Another major problem occurred in the creation of a nuclear reactor. The Fusion process releases an extra neutron with 14 million eV of Energy and a speed of 50000 km per second, and as neutron has zero Charge, it is unaffected by electrostatic interactions. A way to counter is to use light nuclei. A neutron passes a good fraction of its kinetic energy to the nuclei upon collision, slowing it down. What if these neutrons reach the superconductor? Does the collision prove to be disastrous? When a neutron strikes an atom in the Superconductor, it transfers kinetic energy. For a limited time, this increases the current carrying potential of the superconductor, but, eventually, the collision may lead to plummeting current density, which may lead to loss of superconductivity altogether.

Magnetic Levitation using Superconductors

Magnetic Levitation majorly relies on Meissner's Effect. **At about 77K, a sample may be magnetically levitating** without requiring any additional electronic circuit. High Temperature Ceramic oxide superconductors are the primary materials for magnetic suspension. **Ceramic Oxide Superconductors exhibit Type II superconductivity**; therefore, **at magnetic fields below $\mathbf{H_{C1}}$, type II superconductors can prevent magnetically induced penetration**. But how is a stable suspension created?

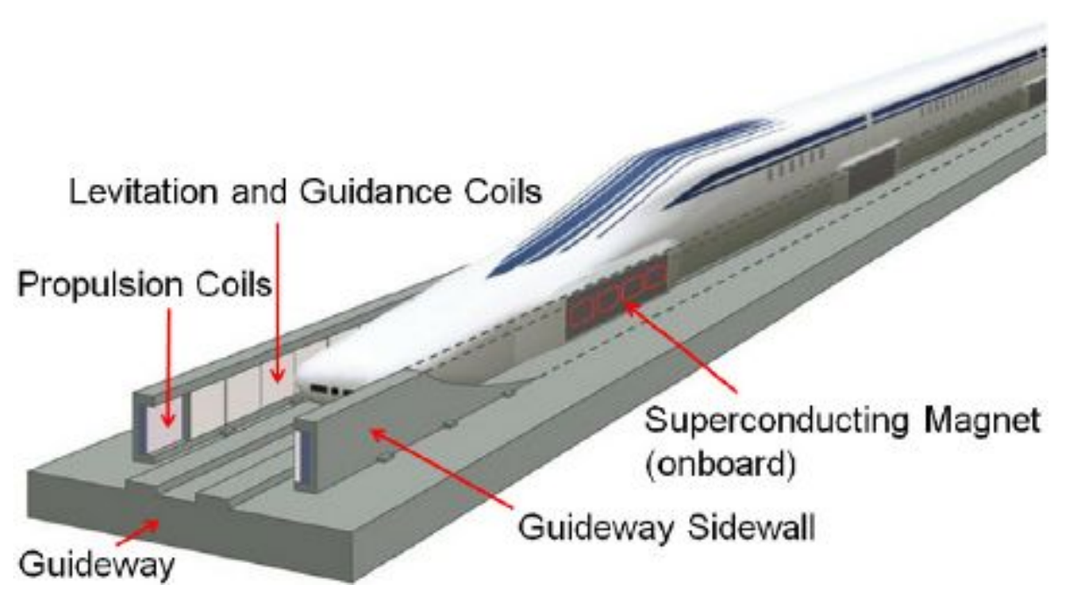

Figure 11. Magnetic Levitating Train Schematic. [Figure on ResearchGate]

When H > $\mathbf{H_{C1}}$, the ceramic oxide is in a 'mixed flux penetration state,' this enables an electromagnet to penetrate and remain pinned at some areas in the material. Consider the **distance between the Electromagnet and Superconductor as *d;*** a change in this distance will 'induce a Supercurrent within the material and creates opposition to any further variation of the magnetic field. Furthermore, **using a Zero Field Cooled (ZFC) procedure**, a superconducting persistence current/shielding current can be induced at the outer rim of the superconducting material by a varying external field. Finally, as the external magnetic field is increasing, **the shielding current will be forced to penetrate the the inner part of the superconductor exerting a Levitation Force (F) on the train** and keeping the train in levitating motion.

The Levitation Force (F)can be calculated by:

$$F = \int J_C \; X \; BdV$$

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