Crash Course in Materials Science of Superconductors

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This document provides basic review of superconducting materials from a materials science & engineering perspective. This entails a very basic review of conductivity, magnetism, and superconductivity theory. The remainder is focused on aspects of specific material systems, such as compositional phases that exhibit superconducting phase, mechanical properties, and processing. High-level review of applications is also provided. The intent of this document is to act as a quick digest for someone who plans to dive deeper into the provided references.

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Some Comments

! Important

These are working notes, so there are bound to be errors. Please keep this in mind while going through the notes. Feel free to email me if you want to provide corrections.

i Note

Much of the notes derived from various sources, please checkout the references.

Tip

If you prefer to view this in a report format, you can download a formatted PDF of this presentation here.

Whats all the fuss

- Why did anyone care to begin with?

  - They didn't. Initially Heike Kamerlingh Onnes[1] and others were just interested in cryogenics.
  - Once they achieved liquid Helium, they asked why note study conductive metals at these temperatures.
  - In 1911 Kamerlingh Onnes started with elemental Mercury, the field of superconductivity (SC) was born.

- Physcist focused on measurement of other elemental solides and a theory.
- Observation of SC in Nb is really what begun technological use.

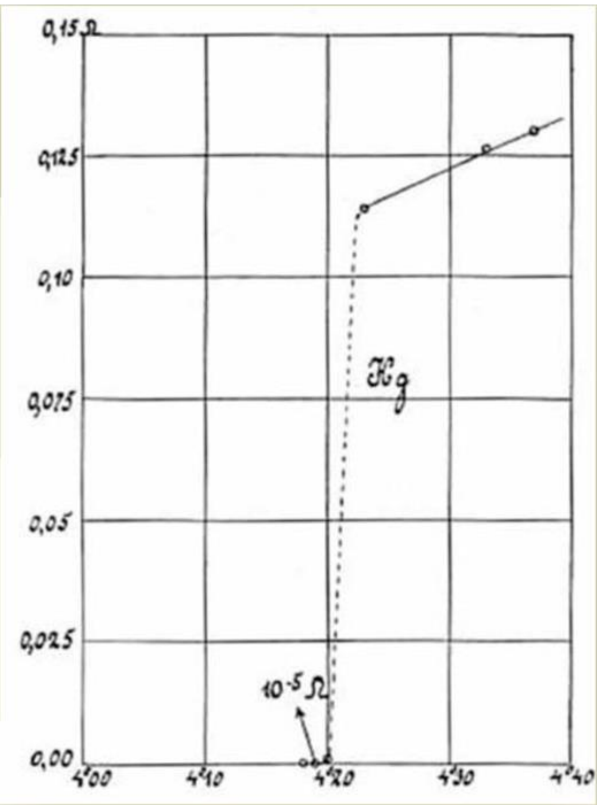

Figure 1: Original plot of Hg transition temperature to SC phase[1].

SC: Superconductivity. Nb: Niobium

Technological Interest

Magnetic Resonance Imaging

- Superconducting coils allow for high magnetic fields.
  - **Stronger Magnets**: Enhanced image quality and resolution.
  - **Energy Efficiency**: Lower operational costs due to zero resistance.

- **Cooling Required**: Increased cost.

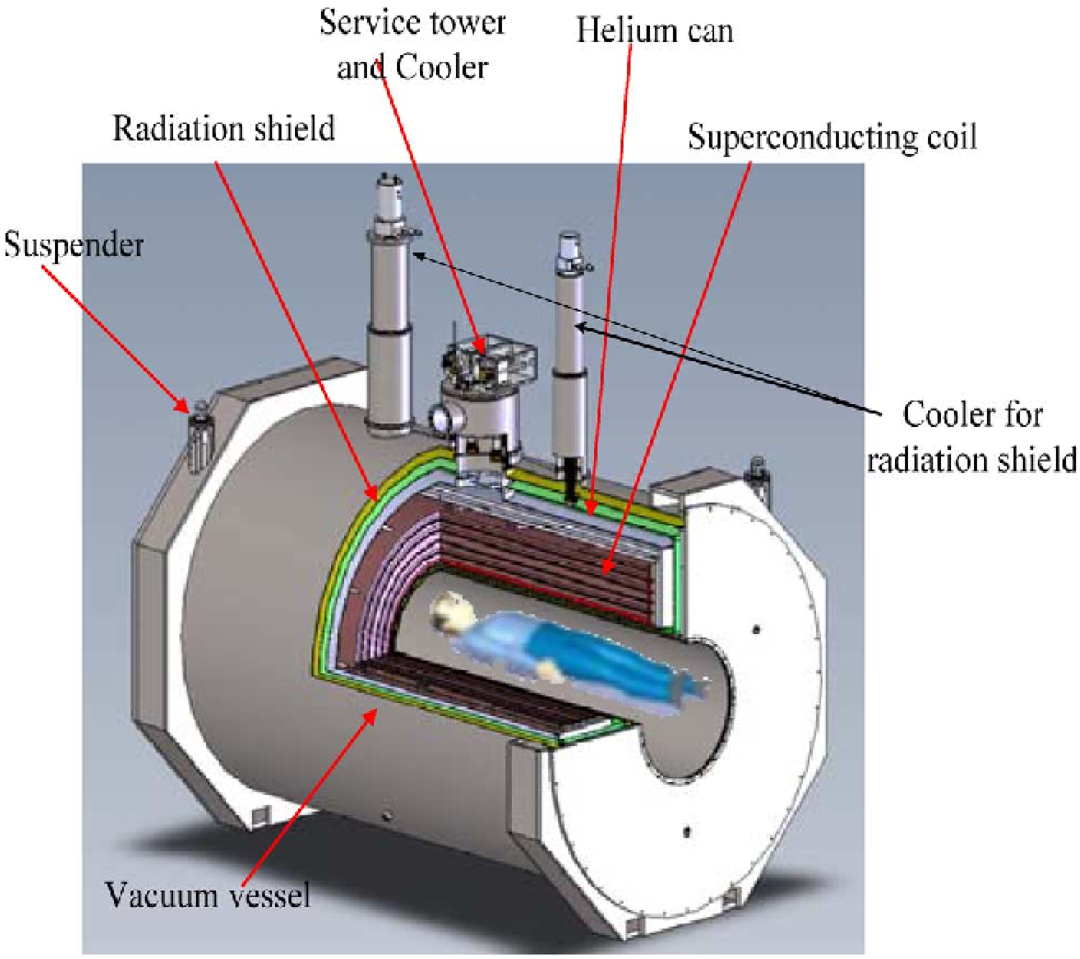

Figure 2: Cut-throught showing MRI machine and SC coils[2].

MagLev Trains

- Superconducting materials enable high-speed rail.
  - **Efficient Levitation**: Frictionless, high-speed travel.
  - **High Current Capacity**: Ideal for powerful electromagnets in propulsion.
  - **Downside**: Cryogenic systems maintain superconducting state.

Energy Storage/Production

- **High Field Strength**: Enables stronger magnetic confinement in fusion.

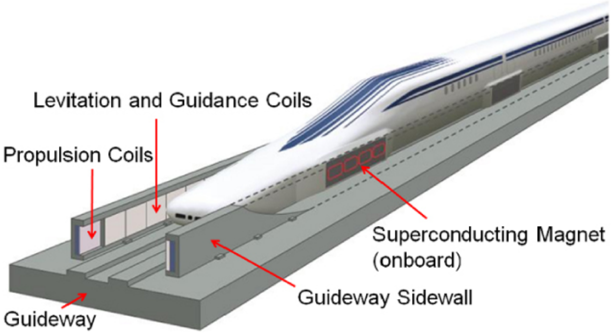

Figure 3: Superconductors are onboard train which interact with propolsion rail coils[3].

- **Zero Resistance**: Increases efficiency in energy storage systems.
- **Cooling Trade-off**: Cryogenic needs offset by gains in efficiency.

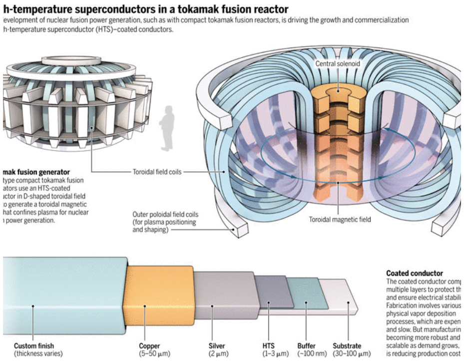

Figure 4: High-temperature SC (ex., REBCO) used in a magnetic fusion torodial device[4].

Most common complaints

- **Cooling Costs**: Cryogenic systems are energy-intensive and expensive.
- **Material Fragility**: Mechanical stresses can degrade superconducting properties.
- **High Costs**: Fabrication and maintenance of superconducting materials are costly.
- **Limited Current Capacity**: Some materials can't sustain high current densities.
- **Material Complexity**: Difficulties in integration with existing technologies.

Many advances have been achieved in last 30 years or so to address these concerns.

> ℹ Note
>
> At this point I won't discuss why these are addressible with advances in refrigeration and processing techonology, but this is how I would approach it . Will touch on this at the very end.

> Many others seek room-temperature (RT) superconductors. These many exist but who knows if they would have other suitable properties or current processing approaches would work.

RT: room-temperature

Basic Theory: Background

- As we saw in Figure 1, there are materials where electrical conductivity drops to "exactly"[1] zero.
- How is this achieved?
  - Well at low-temperature we have Bardeen, Cooper, and Schrieffer (BCS) to thank[5].

- What mechanism did they describe?
  - Describe microscopic superdconducting using quantum theory.
  - **Solution**: Electron Cooper pairs via condesnsate state.
  - Why Pairs? Blame the phonons.

BCS Theory: Bardeen, Cooper, and Schrieffer theory of low-temperature superconductivity.

Basic Theory: Cooper Pairs @ Low Temperature (1/4)

Mathematical Foundation

Hamiltonian: $H = H_0 + H_{\text{int}}$

- H_0: Kinetic energy term

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[1] Here I use exactly in that it is zero within measurement precision. If your device can only measure to 10^{-10} then you show a resistivity value on that order.

- H_{int}: Interaction term

BCS Wave Function:

$$|\Psi_{\text{BCS}}\rangle = \prod_k (u_k + v_k c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow})\,|0\rangle \tag{1}$$

- u_k: Probability amplitude for unoccupied state
- v_k: Probability amplitude for occupied state
- $c^\dagger_{k\uparrow}$, $c^\dagger_{-k\downarrow}$: Electron creation operators

Basic Theory: Cooper Pairs @ Low Temperature (2/4)

Role of Phonons

Electrons interact indirectly via phonons, leading to a net attractive force among pairs of e^-.

$$V(q,\omega) = \frac{2\omega(q)}{q^2}\chi(q,\omega)$$

- $V(q,\omega)$: Electron-phonon interaction
- $\omega(q)$: Phonon frequency
- $\chi(q,\omega)$: Polarizability

Cooper Pairs

- Formed by two electrons with opposite spins and momenta.
- Exhibit Bose-Einstein-like condensation at low temperatures.

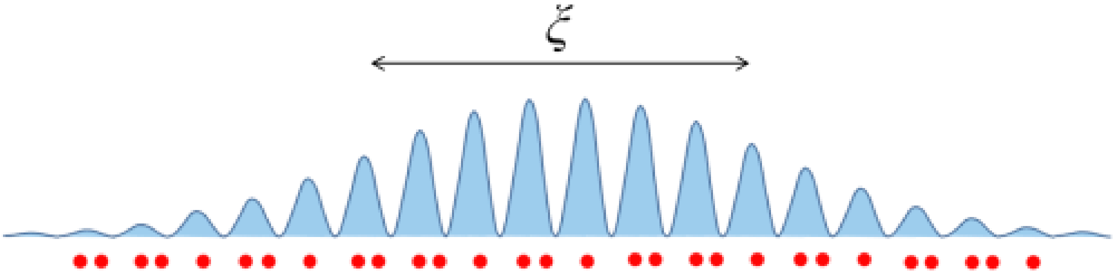

Figure 5: A "static" schematic of real-space cooper pair probablity distribution with coherence length ϵ. Red dots are the distorted lattice positions [2].

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[2] adapted from https://thiscondensedlife.wordpress.com/2015/09/12/draw-me-a-picture-of-a-cooper-pair.

Basic Theory: Cooper Pairs @ Low Temperature (3/4)

Energy Gap

$\Delta = 2\,|V|\,\sqrt{N(0)V}$

- Δ: Energy gap, V: Pairing potential, $N(0)$: Density of states at Fermi level/

Critical Temperature T_c

The temperature below which a material becomes superconducting.

$T_c = \frac{1.13\Delta}{k_B}$

- Δ: Energy gag, k_B: Boltzmann constant

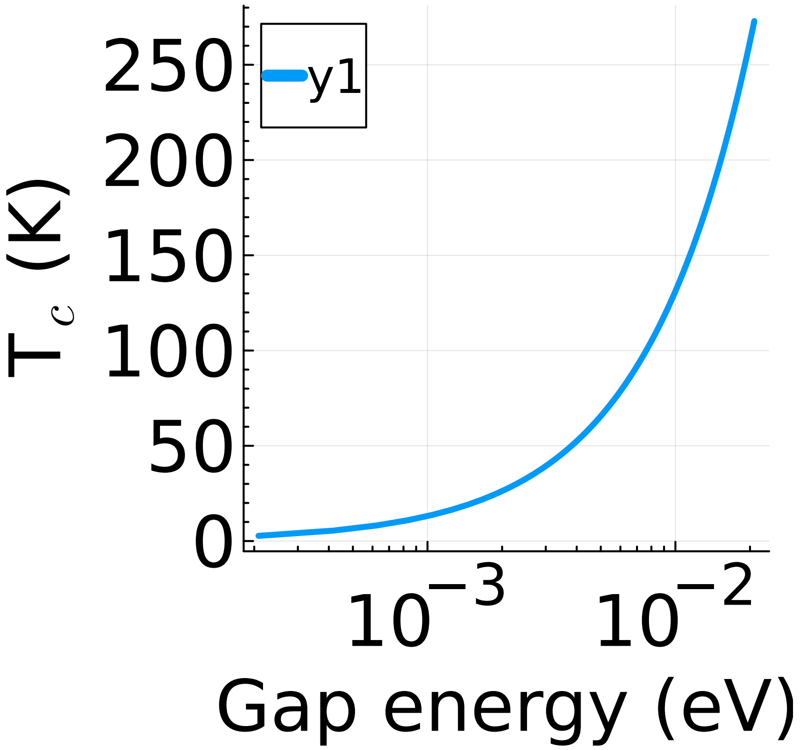

Figure 6: Critical tempature as a function of energy gap.

Basic Theory: Superconducting State Property Predictions

Meissner Effect

The expulsion of magnetic flux lines from the interior of a superconducting material.

London Equations:

$$\vec{J} = -\frac{ne^2}{m}\vec{A} \tag{2}$$

$$\nabla \times \vec{J} = -\frac{ne^2}{m}\vec{B} \tag{3}$$

- $\vec{J}$: Superconducting current density
- $\vec{A}$: Vector potential
- $\vec{B}$: Magnetic field
- n: Density of superconducting carriers
- e: Elementary charge
- m: Electron mass

Basic Theory: Experimental Evidence

- Tunneling experiments
- Specific heat measurements
- Magnetic penetration depth

Superconducting phase

Type I Superconductors

- Exhibit perfect diamagnetism below T_c (Meissner effect)
- Expels all magnetic fields ($H = 0$) due to Cooper pairing
- Critical magnetic field H_c exists, beyond which superconductivity is destroyed
- E.g., Aluminum (Al), Lead (Pb)

Add Figure contrasts Type I and Type II

Type II Superconductors

- Exhibit two critical magnetic fields (H_{c1} and H_{c2})
- Allow magnetic vortices to form between H_{c1} and H_{c2} (mixed state)
- Usually compound or alloy materials with complex structures.
    - Exception are Niobium and Vanadium elemental solids.
- Often high-T_c materials, enabling applications near room temperature
- E.g., Yttrium Barium Copper Oxide (YBCO), Niobium Titanium (NbTi)

Add Figure contrasts Type I and Type II

Backmatter

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Note

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