Why Do We Need Superconductors?

And How Are The Made?

Developed from the talks of:
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And
Dr. Thomas Maier
This photo shows the Meissner effect, the expulsion of a magnetic field from a superconductor in super conducting state.

Image courtesy Argonne National Laboratory
Why are we interested in Superconductors?

Power plants must increase their current to high voltages when transmitting it across country: to overcome energy lost due to **resistance**. Resistance is to electrons moving down a wire as rocks are in a stream. Imagine if we could find a way to remove resistance;

Energy in **would equal** Energy out

Energy Crisis Solved
Why superconductors?

The Facts

• Copper wire can carry 5 Amps/mm²
• Superconductors conduct electricity with significantly less resistance, but they must be cooled for the effect.

• **NbTi can carry 2500 Amps/mm²**
  • A “low temperature” superconductor because it must be cooled to 4.2 Kelvin using liquid Helium (very expensive)

• **YBCO can carry 10,000 Amps/mm²**
  • A “high temperature” superconductor because it must be cooled to 92 Kelvin using liquid Nitrogen (relatively inexpensive to produce)
Other Possibilities
From Superconductors

https://www.youtube.com/watch?v=Z4XEQVnIFmQ
Creating a Superconductor

- Element Properties are important:
  reactivity, toxicity, general properties

<table>
<thead>
<tr>
<th>Element</th>
<th>Metal Radius (pm)</th>
<th>T_{melt} (°C)</th>
<th>T_{boil} (°C)</th>
<th>D_{20°C} (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>197</td>
<td>842</td>
<td>1494</td>
<td>1.55</td>
</tr>
<tr>
<td>Sr</td>
<td>215</td>
<td>769</td>
<td>1382</td>
<td>2.63</td>
</tr>
<tr>
<td>Ba</td>
<td>222</td>
<td>729</td>
<td>1805</td>
<td>3.59</td>
</tr>
</tbody>
</table>
Phase Diagrams Help to Target the Proper Elements

- Eutectic pts
- Congruent reaction
- Peritectic reaction

Managed by UT-Battelle for the U.S. Department of Energy
- The Secret Appears to be in the Crystalline Structure

** Tetragonal structures may be crucial
** ThCr$_2$Si$_2$-type structure may be important

One can explore other Fe-based compounds with this structure:

- EuFe$_2$As$_2$
- KFe$_2$As$_2$
- BaFe$_2$As$_2$
- SrFe$_2$As$_2$
- DyFe$_2$B$_2$
- HoFe$_2$B$_2$
- TmFe$_2$B$_2$
- BaFe$_2$P$_2$
- CaFe$_2$P$_2$
- CeFe$_2$Ge$_2$
- ErFe$_2$B$_2$
- LuFe$_2$B$_2$
- YFe$_2$B$_2$
- CeFe$_2$P$_2$
- GdFe$_2$B$_2$
- TbFe$_2$B$_2$
- CeFe$_2$Si$_2$
- DyFe$_2$Si$_2$
- ErFe$_2$Ge$_2$
- EuFe$_2$P$_2$
- DyFe$_2$Ge$_2$
- ErFe$_2$Si$_2$
- EuFe$_2$Si$_2$
- LaFe$_2$Ge$_2$
- LaFe$_2$P$_2$
- SmFe$_2$Ge$_2$
- UFe$_2$Ge$_2$
- LaFe$_2$Si$_2$
- NdFe$_2$Si$_2$
- TlFe$_2$Se$_2$
- ThFe$_2$Si$_2$
- YFe$_2$Si$_2$
- UFe$_2$P$_2$
- GdFe$_2$Ge$_2$
- NdFe$_2$Ge$_2$
- TbFe$_2$Ge$_2$
- YbFe$_2$Ge$_2$
- LuFe$_2$Si$_2$
- PrFe$_2$Si$_2$
- SmFe$_2$Si$_2$
- TmFe$_2$Si$_2$
- YbFe$_2$Si$_2$
- PrFe$_2$Ge$_2$
- ThFe$_2$Ge$_2$
- HoFe$_2$Si$_2$
- SrFe$_2$P$_2$
- TlFe$_2$Si$_2$
- TbFe$_2$Si$_2$
- TlFe$_2$S$_2$
- UFe$_2$Si$_2$
- ZrFe$_2$Si$_2$
- Preparation Methods are Critical

Fe-based superconductor
Cuprates

- Know how to confine reactions!

<table>
<thead>
<tr>
<th>Elements</th>
<th>Container &amp; tube choices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali &amp; alkaline-earth metals</td>
<td>Ta, steel Al$_2$O$_3$, MgO, BeO</td>
</tr>
<tr>
<td>Al, Ga</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>MgO, Ta, graphite or steel</td>
</tr>
<tr>
<td>Cu, Ag, Au</td>
<td>graphite, MgO, Al$_2$O$_3$, Ta</td>
</tr>
<tr>
<td>Fe, Co, Ni</td>
<td>Al$_2$O$_3$, ZrO$_2$</td>
</tr>
<tr>
<td>Zn, Cd, Hg</td>
<td>Al$_2$O$_3$</td>
</tr>
<tr>
<td>In</td>
<td>Al$_2$O$_3$, Ta</td>
</tr>
<tr>
<td>Rare-earth metals</td>
<td>Ta, Mo, W, BeO</td>
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<tr>
<td>Bi, Sn</td>
<td>Al$_2$O$_3$, SiO$_2$, graphite</td>
</tr>
<tr>
<td>Sb</td>
<td>SiO$_2$, graphite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_{\text{max}}$ ($^\circ$C)</th>
<th>$T_{\text{melting}}$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>borosilicate glass (Pyrex)</td>
<td>515</td>
<td>820</td>
</tr>
<tr>
<td>gold</td>
<td>1013</td>
<td>1064</td>
</tr>
<tr>
<td>silica (quartz)</td>
<td>1200</td>
<td>1853</td>
</tr>
<tr>
<td>platinum</td>
<td>1720</td>
<td>3452 $^\circ$F</td>
</tr>
<tr>
<td>alumina (Al$_2$O$_3$)</td>
<td>1900</td>
<td>2072</td>
</tr>
<tr>
<td>zirconia (ZrO$_2$)</td>
<td>2000</td>
<td>2700</td>
</tr>
<tr>
<td>magnesia (MgO)</td>
<td>2400</td>
<td>2852</td>
</tr>
<tr>
<td>tantalum</td>
<td>1400</td>
<td>3017</td>
</tr>
</tbody>
</table>
Superconducting Materials have Complex Structures

Superconductors

Normal Conductors

La-214
La₂CuO₄
T_c = 40 K

Y-123
YBa₂Cu₃O₇₋δ
T_c = 92 K

Hg-1223
HgBa₂Ca₂Cu₃O₉₊δ
T_c = 133 K

Ti-2223
Tl₂Ba₂Ca₂Cu₃O₁₀
T_c = 125 K

1111
RFeAsO
T_c = 56 K

122
BFe₂As₂, AFe₂Se₂
T_c ≈ 38 K, 45 K

111, 11
AFeAs, FeSe
T_c ≈ 33, 15 K

42622
Sr₄T₂O₆Fe₂As₂
T_c ≈ 37 K

Example:

\[
\text{LaAs} + \frac{x}{3} \text{Co}_3\text{O}_4 + \frac{3-4x}{9} \text{Fe}_2\text{O}_3 + \frac{3-x}{9} \text{Fe} \rightarrow \text{LaFe}_{1-x}\text{Co}_x\text{AsO}
\]

Weigh accurately

Seal into a silica tube

Heat strongly

e.g. 1220 °C (2230 °F)!
Our Superconductivity Research

A research workflow

(a) Decision on a crystal structure
(b) Synthesis
(c) Characterization
The Science of Low Temperature Superconductors
Low Temperature Superconductivity

- At Normal Temperatures
- Electrons in Conductors move independently
- Resistance within the conductor is due to the scattering.
Superconductivity is enabled by the Cooper dance

Cooper Pair Flash Mob
Superconductivity = Cooper dance

- Electrons form “Cooper” pairs. Cooper pairs synchronize electrons eliminating the scattering affect and removing resistance.
But negative charges repel!

So how can electron pairs form?
Everything you wanted to know about pair formation
... in low-temperature superconductors

1. A lattice structure is formed as a part of the creation of the superconducting material.
2. The first electron deforms the lattice of metal ions (ions shift their position due to Coulomb interaction)
3. First electron moves away
4. Second electron is attracted by lattice deformation and moves for former position of first electron
Duplicating a Nobel Prize Winning Experiment
**Low-temperature (conventional) superconductivity is a solved problem**

- We know that ion vibrations cause the electrons to pair

**High-temperature superconductivity is an unsolved problem**

- We know that ion vibrations play no role in superconductivity
- We don’t know (agree) what causes the electrons to pair
The Science of Low Temperature Superconductors is a \textbf{SOLVED} Problem

\textit{High Temperature Superconductors are still Mysterious.}
Complexity in high-temperature superconducting cuprates

- Low-temperature superconductors behave like normal metals above the transition (to superconductor) temperature

- High-temperature superconductors display very strange behavior in their normal state
  - Stripes
  - Charge density waves
  - Spin density waves
  - Inhomogeneities
  - Nematic behavior
  - …

- Many theories have been proposed, most of them are refuted by experiments

“If one looks hard enough, one can find in the cuprates something that is reminiscent of almost any interesting phenomenon in solid state physics.”
(Kivelson & Yao, Nature Mat. ’08)
(Incomplete) list of theories for high-\(T_c\)

- Interlayer tunneling
- Spin fluctuations
- Resonating valence bonds
- Small q phonons
- Flux phases
- Charge fluctuations
- Stripes
- Excitons
- Interlayer Coulomb
- Bipolarons
- Kinetic energy
- Orbital currents
- BCS/BEC crossover
- Plasmons
- Gossamer superconductivity
- Spin liquids
- d-density wave
- Anisotropic phonons
- van Hove singularities
- Marginal Fermi liquid
- Anyon superconductivity
- SO(5)

Credit to:
- Phil Anderson
- Alexei Abrikosov
- Tony Leggett
- Bob Schrieffer
- Karl Müller
- Bob Laughlin
If we can solve Room Temperature Superconductors

- We can generate power from Solar Energy in the Deserts and use it anywhere.
- We can trim our energy budget while increasing our thirst for energy.
- Energy generation methods that are not viable become viable.