Outline

• What is a Superconductor?
• Discovery of Superconductivity
• Meissner Effect
• Type I Superconductors
• Type II Superconductors
• Theory of Superconductivity
• Tunneling and the Josephson Effect
• High-Temperature Superconductors
• Applications of Superconductors
What is a Superconductor?

“A Superconductor has ZERO electrical resistance BELOW a certain critical temperature. Once set in motion, a persistent electric current will flow in the superconducting loop FOREVER without any power loss.”

Magnetic Flux expulsion

A Superconductor EXCLUDES any magnetic fields that come near it.
How “Cool” are Superconductors?

Below 77 Kelvin (-200 °C):
• Some Copper Oxide Ceramics superconduct

Below 4 Kelvin (-270 °C):
• Some Pure Metals e.g. Lead, Mercury, Niobium superconduct

Keeping at 0 °C

Keeping at 77 K

Keeping at 4K

Massachusetts Institute of Technology
The Discovery of Superconductivity 1911

The Nobel Prize in Physics 1913

"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium.

Heike Kamerlingh Onnes
the Netherlands
Leiden University
Leiden, the Netherlands
b. 1853
d. 1926

•http://www.nobel.se/physics/laureates
“As has been said, the experiment left no doubt that, as far as accuracy of measurement went, the resistance disappeared. At the same time, however, something unexpected occurred. The disappearance did not take place gradually but (compare Fig. 17) abruptly. From 1/500 the resistance at 4.2ºK drop to a millionth part. At the lowest temperature, 1.5ºK, it could be established that the resistance had become less than a thousand-millionth part of that at normal temperature.

Thus the mercury at 4.2ºK has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.”

**Heike Kamerlingh Onnes, Nobel Lecture**

- [http://www.nobel.se/physics/laureates](http://www.nobel.se/physics/laureates)
Normal Metal vs Superconductor

Residual resistance

Non-superconductive Metal

Superconductor
## Periodic Table of Elements

**KNOWN SUPERCONDUCTIVE ELEMENTS**

- **Blue = At Ambient Pressure**
- **Green = Only Under High Pressure**

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### Periodic Table

<table>
<thead>
<tr>
<th>1</th>
<th>H</th>
<th>II A</th>
</tr>
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<tr>
<td>2</td>
<td>Li</td>
<td>Be</td>
</tr>
<tr>
<td>11</td>
<td>Na</td>
<td>Mg</td>
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<tr>
<td>3</td>
<td>K</td>
<td>Ca</td>
</tr>
<tr>
<td>37</td>
<td>Rb</td>
<td>Sr</td>
</tr>
<tr>
<td>55</td>
<td>Cs</td>
<td>Ba</td>
</tr>
<tr>
<td>87</td>
<td>Fr</td>
<td>Ra</td>
</tr>
</tbody>
</table>

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### Special Series
- **Lanthanide Series**
- **Actinide Series**

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http://www.superconductors.org/Type1.htm
A Superconductor is more than a perfect conductor, it is a Perfect Diamagnetism

Perfect Conductor $R=0$

Perfect Diamagnet $B=0$

Meissner Effect
Type-I Superconductor
Type-II Superconductor

When a current is applied to a type II superconductor (blue rectangular box) in the mixed state, the magnetic vortices (blue cylinders) feel a force (Lorentz force) that pushes the vortices at right angles to the current flow. This movement dissipates energy and produces resistance [from D. J. Bishop et al., Scientific American, 48 (Feb. 1993)].

http://phys.kent.edu/pages/cep.htm
Upper Critical Fields of Type II Superconductors
BCS Theory of Superconductivity

**The Nobel Prize in Physics 1972**

•“for their jointly developed theory of superconductivity, usually called the BCS-theory”

**ELECTRON-PHONON INTERACTIONS AND SUPERCONDUCTIVITY**

Nobel Lecture, December 11, 1972

By JOHN BARDEEN

Departments of Physics and of Electrical Engineering

University of Illinois Urbana, Illinois

**INTRODUCTION**

Our present understanding of superconductivity has arisen from a close interplay of theory and experiment. It would have been very difficult to have arrived at the theory by purely deductive reasoning from the basic equations of quantum mechanics. Even if someone had done so, no one would have believed that such remarkable properties would really occur in nature. But, as you well know, that is not the way it happened, a great deal had been learned about the experimental properties of superconductors and phenomenological equations had been given to describe many aspects before the microscopic theory was developed.
The Electron-phonon Interaction

The origin of superconductivity in conventional superconductors

Cooper Pairs & Energy Gap

Fig. 5.
A decomposition of the ground state of the superconductor into states in which the pair states $k$ and $k'$ are either occupied or unoccupied.

Superconducting Energy Gap

\[
\frac{N_s(\epsilon V)}{N_o} = \frac{\langle dI/dV \rangle_{na}}{\langle dI/dV \rangle_{ns}}
\]

(18)

Fig. 1.
Schematic diagram illustrating tunneling from a normal metal into a superconductor near \( T \approx 0 \) K. Shown in the lower part of the diagram is the uniform density of states in energy of electrons in the normal metal, with the occupied states shifted by an energy \( eV \) from an applied voltage \( V \) across the junction. The upper part of the diagram shows the density of states in energy in the superconductor with an energy gap \( 2\Delta \). The effect of an increment of voltage \( dV \) giving an energy change \( d\omega \) is to allow tunneling from states in the range \( d\omega \). Since the tunneling probability is proportional to density of states \( N_s(\omega) \), the increment in current \( dI \) is proportional to \( N_s(\omega)d\omega \).

Fig. 2.
Conductance of a Pb-Mg junction as a function of applied voltage (from reference 21).

The Nobel Prize in Physics 1973

"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"

Leo Esaki
1/4 of the prize
Japan
IBM Thomas J. Watson Research Center
Yorktown Heights, NY, USA
b. 1925

Ivar Giaever
1/4 of the prize
USA
General Electric Company
Schenectady, NY, USA
b. 1929 (in Bergen, Norway)

Brian David Josephson
1/2 of the prize
United Kingdom
University of Cambridge
Cambridge, United Kingdom
b. 1940

"for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"

http://www.nobel.se/physics/laureates
Tunneling between a normal metal and another normal metal or a superconductor.

Fig. 3.

Fig. 5.

Tunneling between two superconductors

Fig. 10.
Tunneling between two superconductors with different energy gaps at a temperature larger than 0° K. A. No voltage is applied between the two conductors. B. As a voltage...
Josephson Junction

Superconductor \( \text{Nb} \) \hspace{1cm} \Psi_1 = \sqrt{n_1} e^{i\theta_1} \hspace{1cm} \text{Insulator} \sim 10\text{Å}, \text{Al}_2\text{O}_3 \hspace{1cm} \Psi_2 = \sqrt{n_2} e^{i\theta_2}

- Josephson relations:
  \[ I = I_c \sin \varphi \]
  \[ V = \frac{\Phi_0}{2\pi} \frac{d\varphi}{dt} \]
  \[ \varphi = \theta_2 - \theta_1 \]

- Behaves as a nonlinear inductor:
  \[ V = L_J \frac{dI}{dt}, \]
  \[ L_J = \frac{\Phi_0}{2\pi I_c \cos \varphi} \]
  \[ \Phi_0 = \text{flux quantum} \]
  \[ 483.6 \text{ GHz / mV} \]
**SQUID Magnetometers**

DC SQUID
- Shunt capacitors ~ 1pF
- Jct. Size ~ 1.1μm
- Loop size ~20x20μm²
- $L_{SQUID} \sim 50\text{pH}$
- $I_c \sim 10 \text{ & } 20\mu\text{A}$
High-Temperature Superconductivity

The Nobel Prize in Physics 1987

"for their important break-through in the discovery of superconductivity in ceramic materials"

J. Georg Bednorz

K. Alexander Müller

J. Georg Bednorz

K. Alexander Müller

1/2 of the prize

1/2 of the prize

b. 1950

b. 1927

Federal Republic of Germany

Switzerland

IBM Zurich Research Laboratory

IBM Zurich Research Laboratory

Rüschlikon, Switzerland

Rüschlikon, Switzerland

http://www.nobel.se/physics/laureates

Figure 1.5. Low-temperature resistivity of a sample with $x(Ba) = 0.75$, recorded for different current densities. From [119], © Springer-Verlag 1986.
High-Temperature Superconductors

Figure 1.3. Evolution of the superconductive transition temperature subsequent to the discovery of the phenomenon. From [1.29]. © 1987 by the American Association for the Advancement of Science.

Figure 1.4. Resistivity of a single-phase $\gamma$Ba$_2$Cu$_3$O$_7$ sample as a function of temperature.

Perovskite Structure

[Diagram of Perovskite Structure]

High-Temperature Superconductor
Uses for Superconductors

• Magnetic Levitation allows trains to “float” on strong superconducting magnets (MAGLEV in Japan, 1997)

• To generate huge magnetic field e.g. for Magnetic Resonance Imaging (MRI)

• A SQUID (Superconducting Quantum Interference Device) is the most sensitive magnetometer. (sensitive to 100 billion times weaker than the Earth’s magnetic field)

• Quantum Computing

Picture source: http://www.superconductors.org
## Large-Scale Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Technical Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power cables</td>
<td>High current densities</td>
</tr>
<tr>
<td>Current Limiters</td>
<td>Uses highly nonlinear nature of transition</td>
</tr>
<tr>
<td>Transformers</td>
<td>High current densities and magnetic fields, has lower losses</td>
</tr>
<tr>
<td>Motors/Generators</td>
<td>Smaller weight and size, lower losses</td>
</tr>
<tr>
<td>Energy Storage Magnets</td>
<td>Need high fields and currents</td>
</tr>
<tr>
<td></td>
<td>Smaller weight and size, lower losses</td>
</tr>
<tr>
<td>NMR magnets (MRI)</td>
<td>Ultra high field stability, large air gaps</td>
</tr>
<tr>
<td>Cavities for Accelerators</td>
<td>High microwave powers</td>
</tr>
<tr>
<td>Magnetic bearings</td>
<td>Low losses, self-controlled levitation</td>
</tr>
</tbody>
</table>

Adapted from http://www.conectus.org/xxroadmap.html
Phase Diagram of a Type II Superconductor

Phase Diagram

http://www.futurescience.com/manual/sc1000.html#C
## Small-Scale Applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Technical Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave filters in celluar stations</td>
<td>Low losses, smaller size, sharp filtering</td>
</tr>
<tr>
<td>Passive microwave devices, Resonators for oscillators</td>
<td>Lower surface losses, high quality factors, small size</td>
</tr>
<tr>
<td>Far-infrared bolometers</td>
<td>nonlinear tunneling SIS curves, high sensitivity</td>
</tr>
<tr>
<td>Microwave detectors</td>
<td>Uses nonlinear tunneling SIS curves, high conversion efficiency for mixing</td>
</tr>
<tr>
<td>X-ray detectors</td>
<td>High photon energy resolution</td>
</tr>
<tr>
<td>SQUID Magnetometers: Magneto-encephalography, NDT</td>
<td>Ultra-high sensitivity to magnetic fields</td>
</tr>
<tr>
<td>Voltage Standards</td>
<td>Quantum precision</td>
</tr>
<tr>
<td>Digital Circuits (SFQ)</td>
<td>Up to 750 GHz, ultra-fast, low-power</td>
</tr>
</tbody>
</table>

Adapted from http://www.conectus.org/xxroadmap.html
Economic Outlook

$40 billion

• http://www.superconductors.org/conectus.pdf
The Promise of a Quantum Computer

A Quantum Computer …

• Offers exponential improvement in speed and memory over existing computers

• Capable of reversible computation

• e.g. Can factorize a 250-digit number in seconds while an ordinary computer will take 800 000 years!

Current Research in my group focuses on Quantum Computation using Superconductors
The “Magic” of Quantum Mechanics

States 0 and 1 are stored and processed AT THE SAME TIME

\[ |0\rangle + |1\rangle \]

Parallel Computation

Exponential Speedup to get Answers

Massachusetts Institute of Technology
The Superconducting “Quantum Bit”

- An External Magnet can induce a current in a superconducting loop.

- The induced current can be in the opposite direction if we carefully choose a different magnetic field this time.

- To store and process information as a computer bit, we assign:
  
  | Clockwise | as state | 0 ⟩ |
  | Anti-clockwise | as state | 1 ⟩ |
Persistent Current Qubit

- Depending on the direction of the current, state $|0\rangle$ and state $|1\rangle$ will add a different magnetic field to the external magnet.

- This difference is very small but can be distinguished by the extremely sensitive SQUID sensor.
Our Approach to Superconductivity

Superconductor as a perfect conductor & perfect diamagnet

Macroscopic Quantum Model $\Psi(r)$

Supercurrent Equation $J_s(r)$

Type II Superconductivity

Large-Scale Applications

Josephson Equations

Small-Scale Applications

Ginzburg-Landau

$\Psi(r) = |\Psi(r)|^2 e^{i\theta(r,t)}$

BCS