6.763 Applied Superconductivity Lecture 1

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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."

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Magnetic Flux explusion

A ***Superconductor*** *EXCLUDES* any magnetic fields that come near it.

How "Cool" are Superconductors?

Below **77 Kelvin** (-200 ºC):

• Some Copper Oxide Ceramics superconduct

Below **4 Kelvin** (-270 ºC):

• Some Pure Metals e.g. Lead, Mercury, Niobium superconduct

Keeping at 0 ºC

Keeping at 77 K

Keeping at 4K

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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"

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Please see:
http://nobelprize.org/physics/laureates/1913/onnes-lecture.pdf

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Please see:
http://nobelprize.org/physics/laureates/1913/index.html

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

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

Discovery of Superconductivity

"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 4.2^{o}K drop to a millionth part. At the lowest temperature, 1.5^{o}K, it could be established that the resistance had become less than a thousand-millionth part of that at normal temperature.

Thus the mercury at 4.2^{o}K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity."

Heike Kamerlingh Onnes, Nobel Lecture

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Please see: Figure 1.1, page 3, from Orlando, T., and K. Delin. *Foundations of Applied Superconductivity.* Reading, MA: Addison-Wesley, 1991. ISBN: 0201183234.

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

Normal Metal vs Superconductor

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Please see: http://www.superconductors.org/Type1.htm

Periodic Table of Elements

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Please see: http://www.superconductors.org/Type1.htm

•http://www.superconductors.org/Type1.htm

A Superconductor is more than a perfect conductor, it is a Perfect Diamagnetism

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Type-I Superconductor

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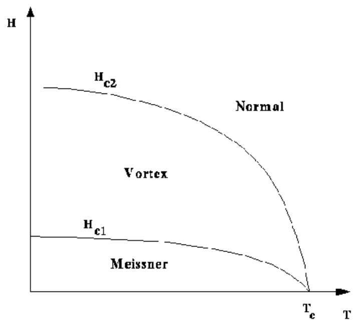
Type-II Superconductor



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Please see: "A current-carrying type II superconductor in the mixed state" from http://phys.kent.edu/pages/cep.htm

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

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BCS Theory of Superconductivity

The Nobel Prize in Physics 1972

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

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Please see: http://nobelprize.org/physics/laureates/1972/index.html

John Bardeen	Leon Neil Cooper	John Robert Schrieffer
1/3 of the prize	1/3 of the prize	1/3 of the prize
USA	USA	USA
University of Illinois Urbana, IL, USA	Brown University Providence, RI, USA	University of Pennsylvania Philadelphia, PA, USA
b. 1908 d. 1991	b. 1930	b. 1931

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

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.

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The Electron-phonon Interaction

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The origin of superconductivity in conventional superconductors

http://www.physics.carleton.ca/courses/75.364/mp-2html/node16.html

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Cooper Pairs & Energy Gap

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Please see: Figure 5 and figure 6 from http://nobelprize.org/physics/laureates/1972/cooper-lecture.html

http://www.nobel.se/physics/laureates/1972/cooper-lecture.pdf

Superconducting Energy Gap

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Please see: Figure 1 and figure 2 from http://nobelprize.org/physics/laureates/1972/bardeen-lecture.html

http://www.nobel.se/physics/laureates/1972/bardeen-lecture.pdf

The Nobel Prize in Physics 1973

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

"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"

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Please see: Figure 1 from http://nobelprize.org/physics/laureates/1973/giaever-lecture.html

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Please see: http://nobelprize.org/physics/laureates/1973/index.html

Leo Esaki	Ivar Giaever	Brian David Josephson
1/4 of the prize	1/4 of the prize	1/2 of the prize
Japan	USA	United Kingdom
IBM Thomas J. Watson Research Center Yorktown Heights, NY, USA	General Electric Company Schenectady, NY, USA	University of Cambridge Cambridge, United Kingdom
b. 1925	b. 1929 (in Bergen, Norway)	b. 1940

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

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Tunneling between a normal metal and another normal metal or a superconductor

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Please see: Figures 3 and 4 from http://nobelprize.org/physics/laureates/1973/giaever-lecture.html

http://www.nobel.se/physics/laureates/1973/giaever-lecture.pdf

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Tunneling between two superconductors

Giaever Tunneling

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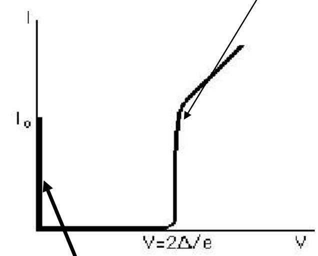
Please see: Figure 10 from http://nobelprize.org/physics/laureates/1973/giaever-lecture.html



Josephson Tunneling

Josephson Junction

Superconductor Nb

$\Psi_1 = \sqrt{n_1} e^{i\theta_1}$

$\Psi_2 = \sqrt{n_2} e^{i\theta_2}$

Insulator ~10Å, Al_2O_3

- Josephson relations:

$$I = I_c \sin\varphi$$

$$V = \frac{\Phi_0}{2\pi}\frac{d\varphi}{dt}$$

$$\varphi = \theta_2 - \theta_1 - \frac{2\pi}{\Phi_0}\int_2^1 \vec{A}(r,t)\cdot d\vec{l}$$

- Behaves as a nonlinear inductor:

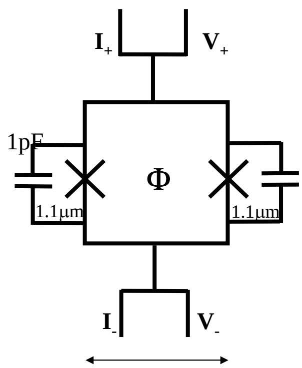
$$V = L_J \frac{dI}{dt},$$

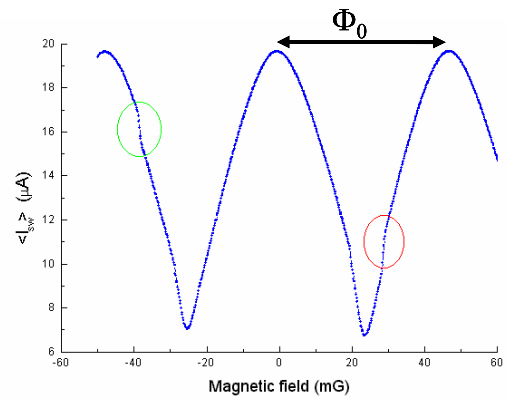
where $L_J = \dfrac{\Phi_0}{2\pi\, I_c \cos\varphi}$

Φ_0 = flux quantum

483.6 GHz / mV

SQUID Magnetometers





<u>DC SQUID</u>
Shunt capacitors ~ 1pF
Jct. Size ~ 1.1μm
Loop size ~20x20μm²
L_{SQUID} ~ 50pH
I_c~10 & 20μA

High-Temperature Superconductivity

The Nobel Prize in Physics 1987

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

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Please see: http://nobelprize.org/physics/laureates/1987/index.html

J. Georg Bednorz
1/2 of the prize
Federal Republic of Germany
IBM Zurich Research Laboratory
Rüschlikon, Switzerland
b. 1950

K. Alexander Müller
1/2 of the prize
Switzerland
IBM Zurich Research Laboratory
Rüschlikon, Switzerland
b. 1927

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Please see: Figure 1.5 from http://nobelprize.org/physics/laureates/1987/bednorz-lecture.html

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

High-Temperature Superconductors

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Please see: Figures 1.13 and 1.14 from http://nobelprize.org/physics/laureates/1987/bednorz-lecture.html

http://www.nobel.se/physics/laureates/1987/bednorz-muller-lecture.pdf

Perovskite Structure

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Please see: Images from http://cst-www.nrl.navy.mil/lattice/struk/perovskite.html

•http://cst-www.nrl.navy.mil/lattice/struk/perovskite.html

High-Temperature Superconductors

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Uses for Superconductors

- Magnetic Levitation allows trains to "float" on strong superconducting magnets (MAGLEV in Japan, 1997)

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- 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

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

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

Recent Advances in Superconductivity

call for papers for 2006 MRS meeting

High-temperature superconductors have been featured at MRS meetings since their discovery in 1986. Twenty years later, the progress both on the fundamental understanding of these materials and the path towards their industrial applications has been impressive. **First-generation wires are now routinely produced in kilometer lengths and used in a variety of large-scale prototypes of practical devices**, while the scale-up of second-generation wires (RE123-based coated conductors) for industrial manufacturing is progressing at a fast pace. These achievements have been made possible by cutting-edge developments in materials science and technology. Coated conductors are composites of nanoscale layers of various materials and functionalities; and the understanding of issues concerning textured templates, complex oxide epitaxy, interfacial reactions, metal-oxide interfaces, crystal chemistry, defect characterization, and diffusion barriers is essential for the optimization of their properties. A topic of present large interest is the improvement of the in-field critical current by introduction of appropriate vortex pinning centers. It is now clear that **large improvements can be obtained through the nano-engineering of several types of defects**. As the technology approaches maturity, new problems such as ac losses and thermal stabilization will become increasingly important. **Superconducting MgB2 also attracts large interest** due to its high-transition temperature (highest among binary compounds), chemical simplicity, low cost of the raw materials, and absence of weak-link limitations that allows the use of mature powder-in-tube technology to fabricate long wires. The inclusion of MgB2 presentations in the symposium will bring together both communities and will encourage the discussion of problems that are common to all superconducting wires. <http://www.mrs.org/meetings/spring2006/program/s06_cfp_hh.html>

Phase Diagram of a Type II Superconductor

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Pleas see: Phase Diagram from http://www.futurescience.com/manual/sc1000.html#C

•http://www.futurescience.com/manual/sc1000.html#C

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Small-Scale Applications

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

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

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Nanowire single-photon detector

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•**K. Berggren, MIT**

Large-area single-photon detector

Image removed for copyright reasons.

•**K. Berggren, MIT**

Economic Outlook

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Please see: Worldwide Markets for Superconductivity from
http://www.superconductors.org/conectus.pdf

•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

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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

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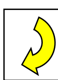
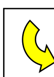
- To store and process information as a computer bit, we assign:

 as state $|\,\mathbf{0}\,\rangle$

clockwise

 as state $|\,\mathbf{1}\,\rangle$

Anti-clockwise

Persistent Current Qubit

• Depending on the direction of the current, state |0⟩ and state |1⟩ will *add* a different magnetic field to the external magnet

Image removed for copyright reasons.

• This difference is very small but can be distinguished by the extremely sensitive SQUID sensor

Our Approach to Superconductivity

Classical

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

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

↓

Microscopic Quantum

BCS

Macroscopic Quantum Model