Physics 5K Lecture 7 Friday May 18, 2012

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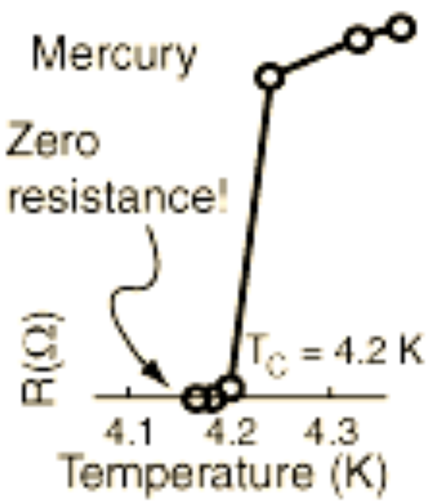
Superconductivity
101st Anniversary Year



If mercury is cooled below 4.1 K, it loses all electric resistance. This discovery of superconductivity by H. Kammerlingh Onnes in 1911 was followed by the observation of other metals which exhibit zero resistivity below a certain critical temperature. The fact that the resistance is zero has been demonstrated by sustaining currents in superconducting lead rings for many years with no measurable reduction. An induced current in an ordinary metal ring would decay rapidly from the dissipation of ordinary resistance, but superconducting rings had exhibited a decay constant of over a billion years!

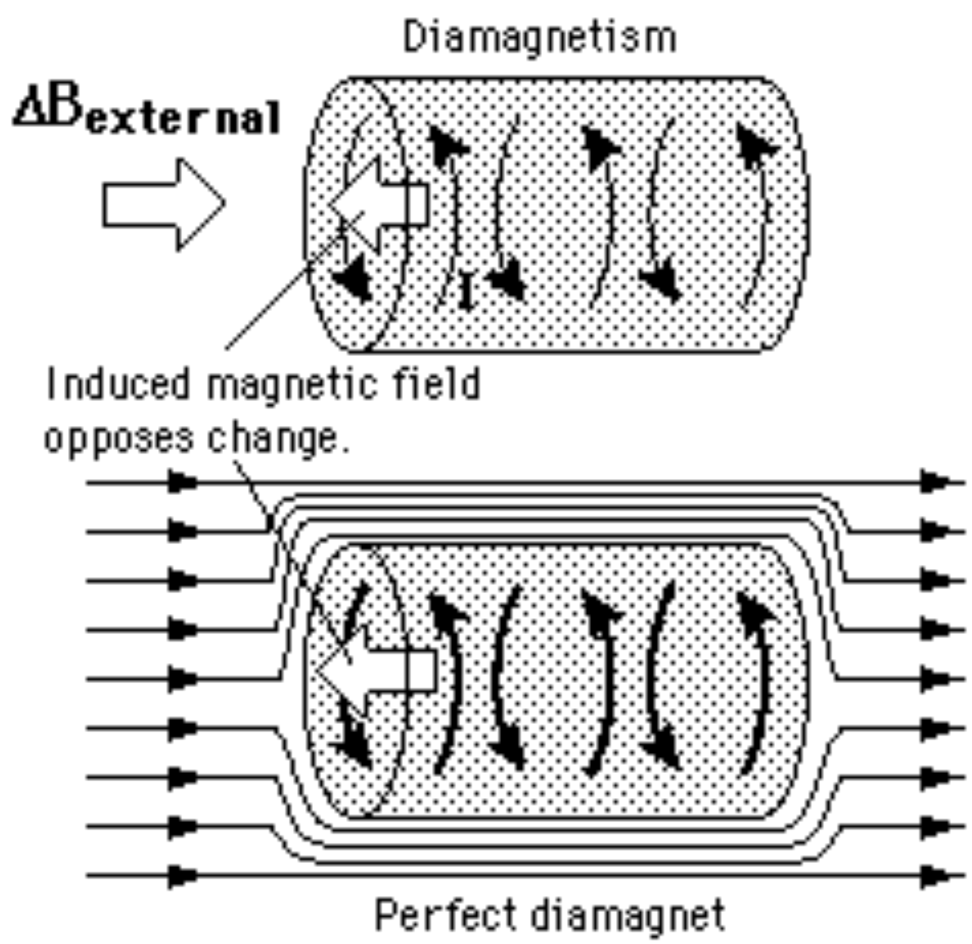
One of the properties of a superconductor is that it will exclude magnetic fields, a phenomenon called the Meissner effect.

The disappearance of electrical resistivity was modeled in terms of electron pairing in the crystal lattice by John Bardeen, Leon Cooper, and Robert Schrieffer in what is commonly called the BCS theory.

A new era in the study of superconductivity began in 1986 with the discovery of high critical temperature superconductors.

Material	T-Critical
Gallium	1.1 K
Aluminum	1.2 K
Indium	3.4 K
Tin	3.7 K
Mercury	4.2 K
Lead	7.2 K
Niobium	9.3 K
Niobium-Tin	17.9 K
La-Ba-Cu-oxide	30 K
Y-Ba-Cu-oxide	92 K
Tl-Ba-Cu-oxide	125 K

Perfect Diamagnetism

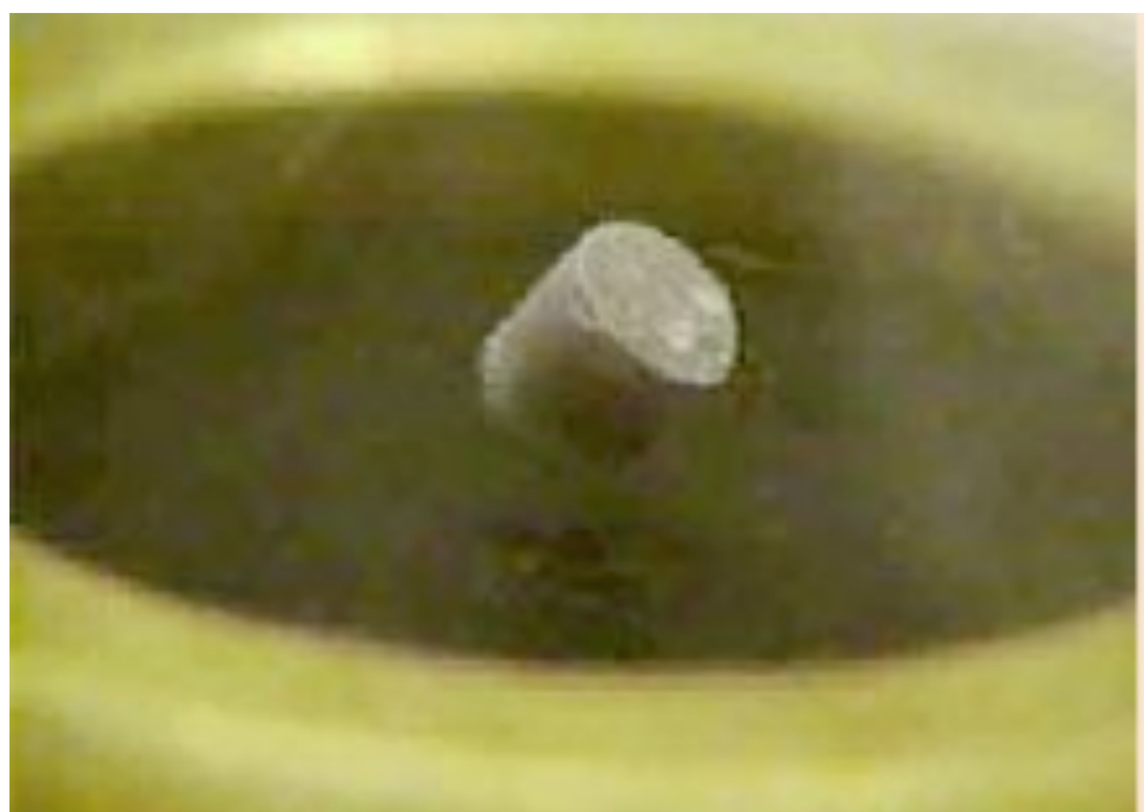


A conductor will oppose any change in externally applied magnetic field. Circulating currents will be induced to oppose the buildup of magnetic field in the conductor (Lenz's law). In a solid material, this is called diamagnetism, and a perfect conductor would be a perfect diamagnet. That is, induced currents in it would meet no resistance, so they would persist in whatever magnitude necessary to perfectly cancel the external field change. A superconductor is a perfect diamagnet, but there is more than this involved in the Meissner effect.

Magnetic Levitation

Magnetic fields are actively excluded from superconductors (Meissner effect). If a small magnet is brought near a superconductor, it will be repelled becaused induced supercurrents will produce mirror images of each pole. If a small permanent magnet is placed above a superconductor, it can be levitated by this repulsive force. The black ceramic material in the illustrations is a sample of the yttrium based superconductor.

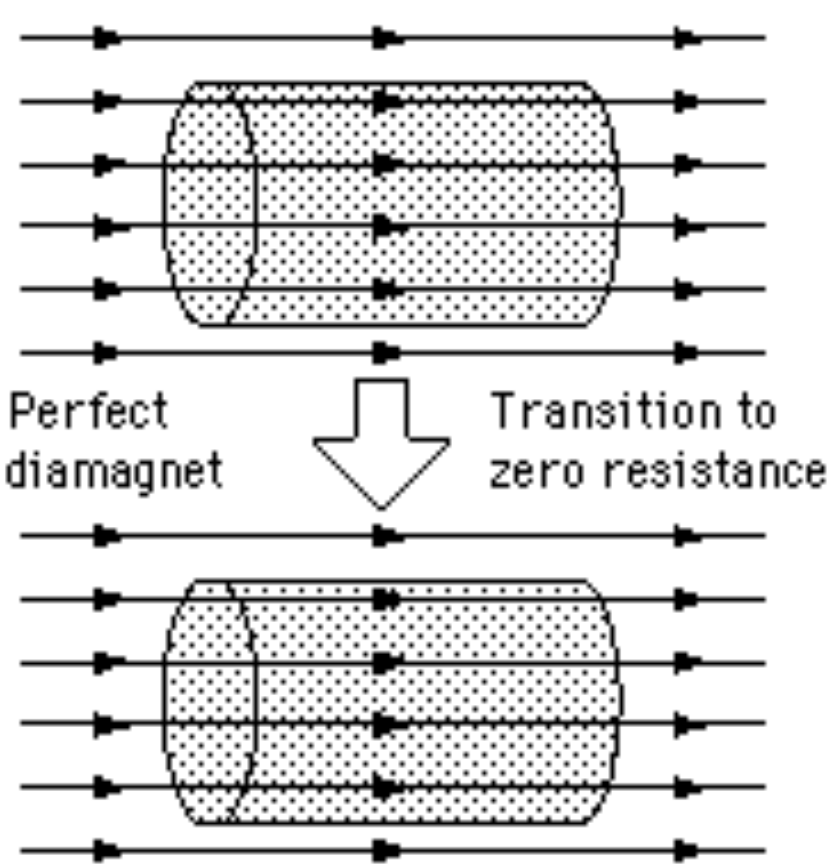
By tapping with a sharp instrument, the suspended magnet can be caused to oscillate or rotate. This motion is found to be damped, and will come to rest in a few seconds.



The Meissner Effect

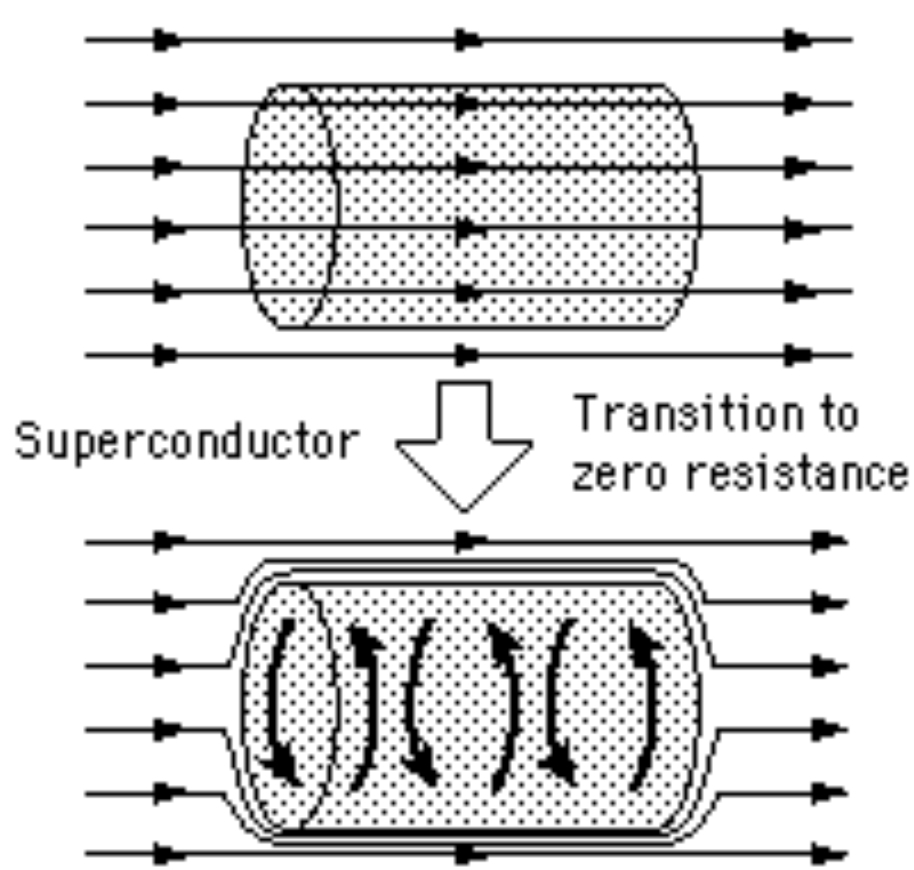
Perfect Diamagnet

If a conductor already had a steady magnetic field through it and was then cooled through the transition to a zero resistance state, becoming a perfect diamagnet, the magnetic field would be expected to stay the same.



Superconductor

Remarkably, the magnetic behavior of a superconductor is distinct from perfect diamagnetism. It will actively exclude any magnetic field present when it makes the phase change to the superconducting state.

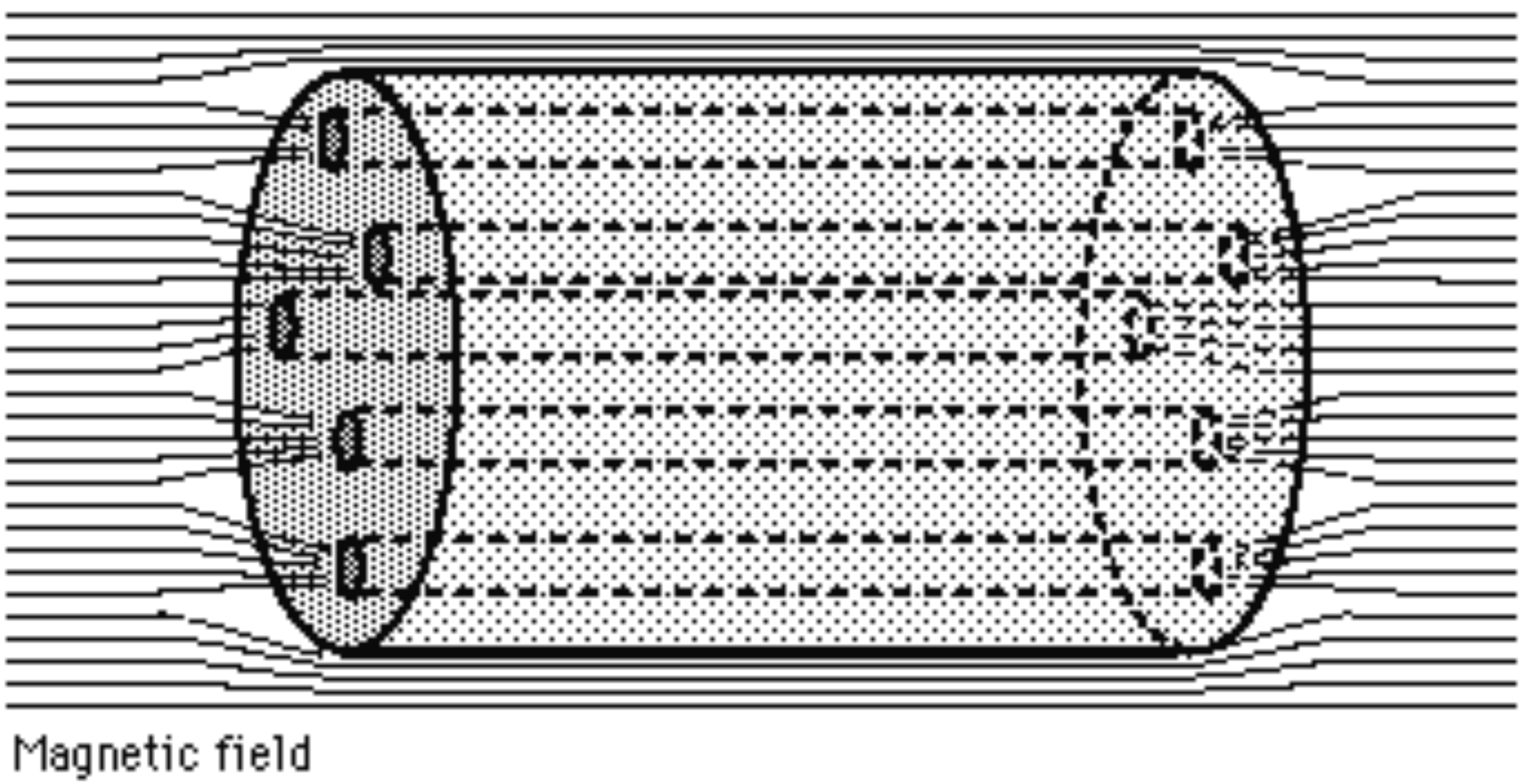


Inside a superconductor, a photon carrying a magnetic field effectively gets a mass, which produces an exponential decrease of the magnetic field as it penetrates into the superconductor.

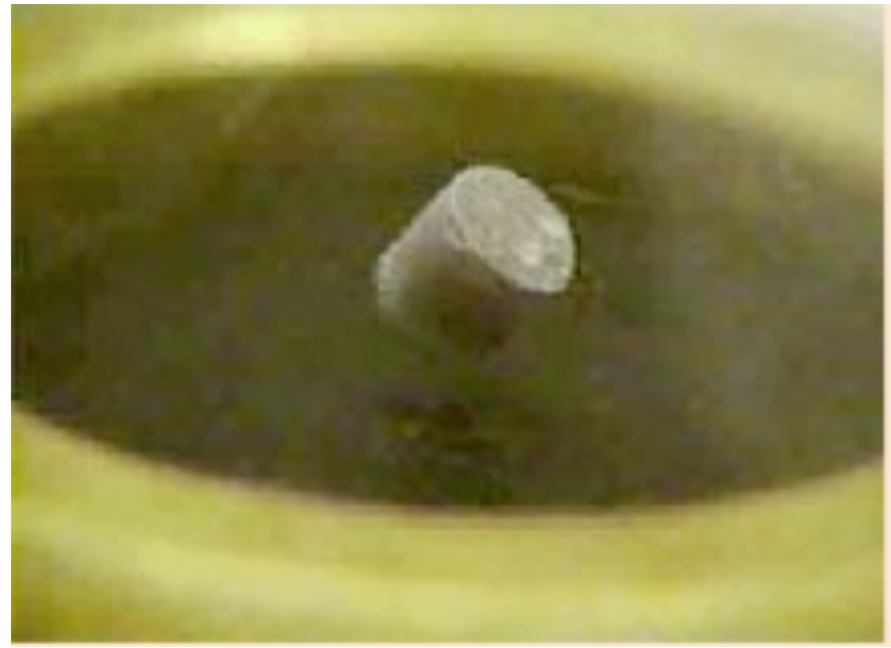
This is a solid state prototype for the "Higgs phenomenon" whereby the weak interaction particles $W^{\pm}$ and Z^0 get a mass.

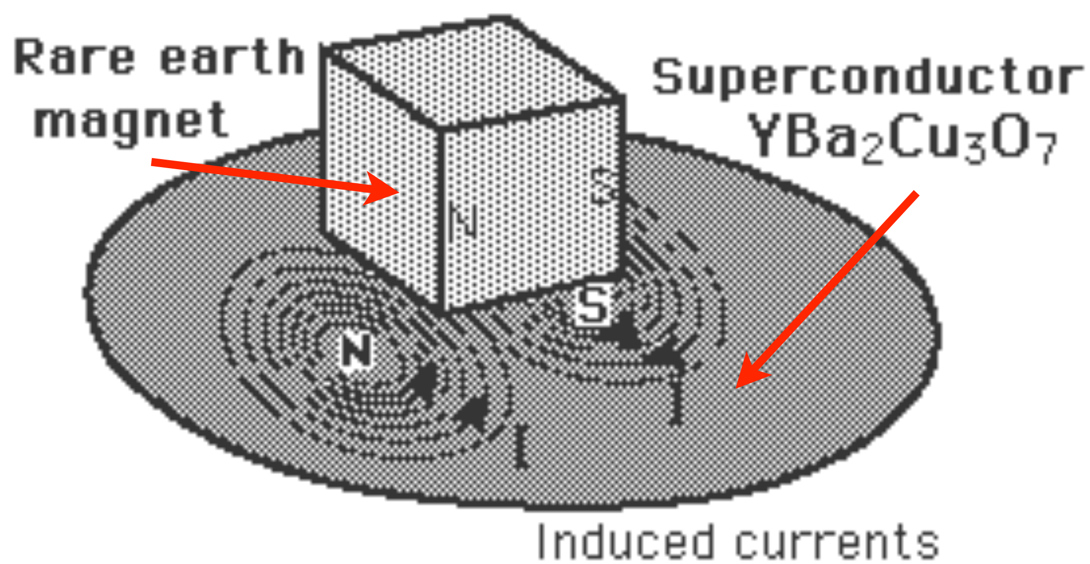
Mixed-State Meissner Effect

In Type II superconductors the magnetic field is not excluded completely, but is constrained in filaments within the material. These filaments are in the normal state, surrounded by supercurrents in what is called a vortex state. Such materials can be subjected to much higher external magnetic fields and remain superconducting.



The Meissner effect in superconductors like this black ceramic yttrium based superconductor acts to exclude magnetic fields from the material. Since the electrical resistance is zero, supercurrents are generated in the material to exclude the magnetic fields from a magnet brought near it. The currents which cancel the external field produce magnetic poles which mirror the poles of the permanent magnet, repelling them to provide the lift to levitate the magnet.



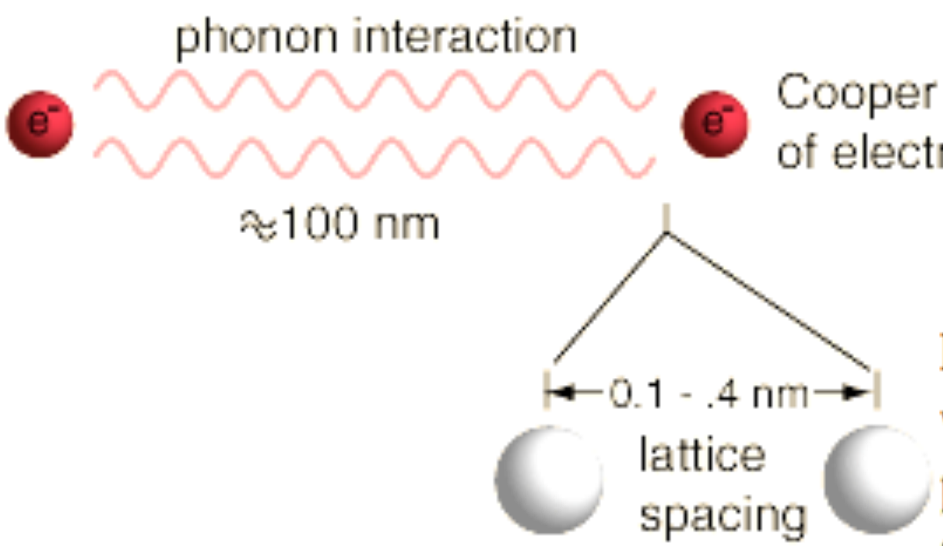


The levitation process is quite remarkable. Since the levitating currents in the superconductor meet no resistance, they can adjust almost instantly to maintain the levitation. The suspended magnet can be moved, put into oscillation, or even spun rapidly and the levitation currents will adjust to keep it in suspension.

BCS Theory of Superconductivity

The properties of Type I superconductors were modeled successfully by the efforts of John Bardeen, Leon Cooper, and Robert Schrieffer in what is commonly called the BCS theory. A key conceptual element in this theory is the pairing of electrons close to the Fermi level into Cooper pairs through interaction with the crystal lattice. This pairing results from a slight attraction between the electrons related to lattice vibrations; the coupling to the lattice is called a phonon interaction.

John Bardeen | Leon Neil Cooper | John Robert Schrieffer



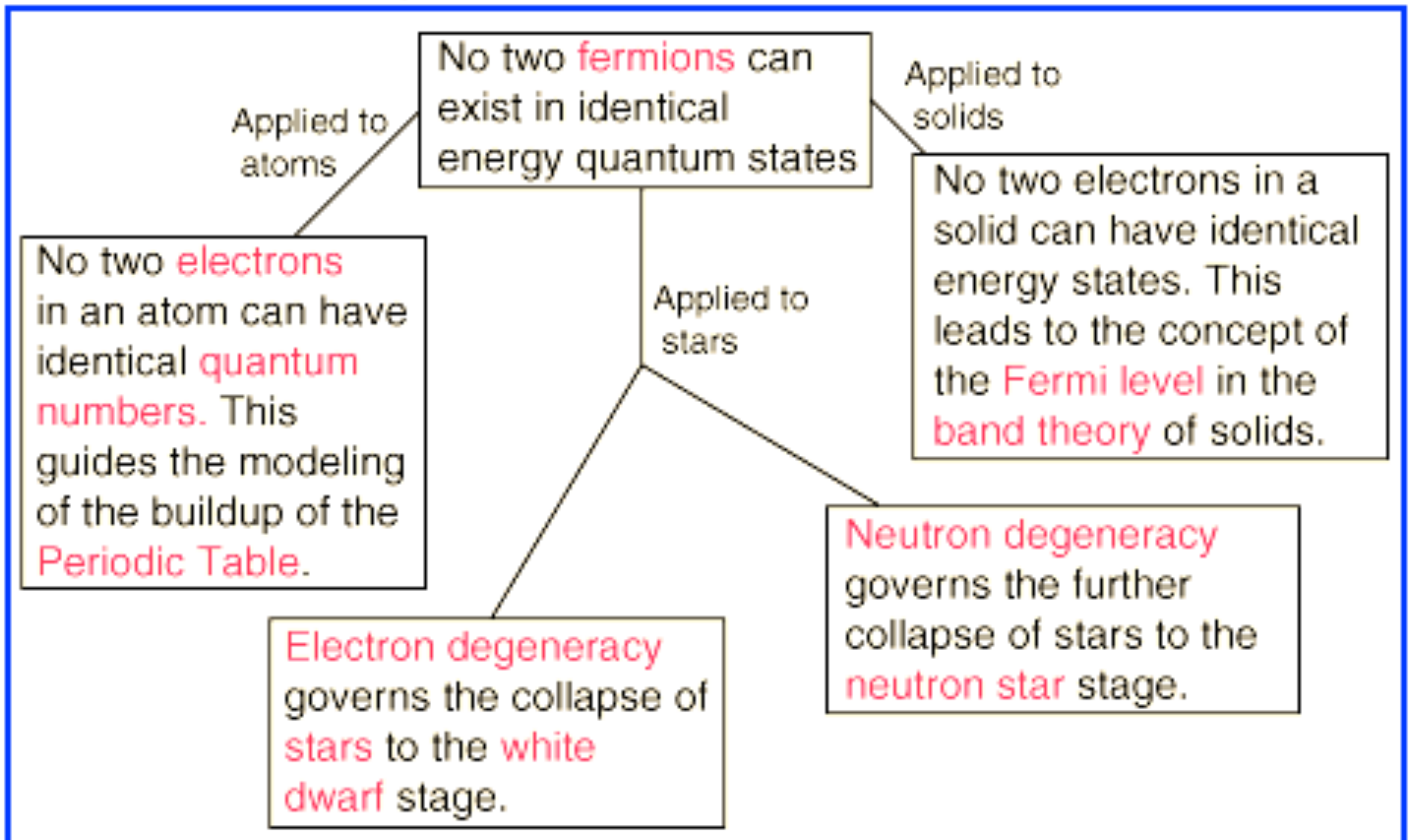
Pairs of electrons can behave very differently from single electrons which are fermions and must obey the Pauli exclusion principle. The pairs of electrons act more like bosons which can condense into the same energy level. The electron pairs have a slightly lower energy and leave an energy gap above them on the order of .001 eV which inhibits the kind of collision interactions which lead to ordinary resistivity. For temperatures such that the thermal energy is less than the band gap, the material exhibits zero resistivity.

Bardeen, Cooper, and Schrieffer received the Nobel Prize in 1972 for the development of the theory of superconductivity.

Fermions (review)

Fermions are particles which have half-integer spin and therefore are constrained by the Pauli exclusion principle. Particles with integer spin are called bosons. Fermions incude electrons, protons, neutrons. The wavefunction which describes a collection of fermions must be antisymmetric with respect to the exchange of identical particles, while the wavefunction for a collection of bosons is symmetric.

Pauli Exclusion Principle Applications



Bosons

Bosons are particles that have integer spin and therefore are not constrained by the Pauli exclusion principle like the half-integer spin fermions. The energy distribution of bosons is described by Bose-Einstein statistics. The quantum mechanical wavefunction that describes a collection of bosons must be symmetric with respect to the exchange of identical particles, while the wavefunction for a collection of fermions is antisymmetric (i.e., it changes sign if any two identical fermions are interchanged). Antisymmetry leads to the Pauli exclusion principle for fermions, while symmetry favors many bosons being in the same state.

At low temperatures, bosons can behave very differently than fermions because an unlimited number of them can collect into the same energy state. The collection into a single state is called Bose-Einstein condensation. It is responsible for the phenomenon of superfluidity in liquid helium. Coupled fermions can also act as bosons. In the BCS Theory of superconductivity, coupled pairs of electrons ("Cooper pairs") act like bosons and condense into a state with zero electrical resistance.

Bosons include photons, and the characterization of photons as particles with frequency-dependent energy given by the Planck relationship $E = h\nu$ allowed Einstein to apply Bose-Einstein statistics to explain the thermal radiation from a hot cavity. That photons are bosons also leads to stimulated emission and lasers: (LASER = Light Amplification by Stimulated Emission of Radiation).

Experimental Support: BCS Theory

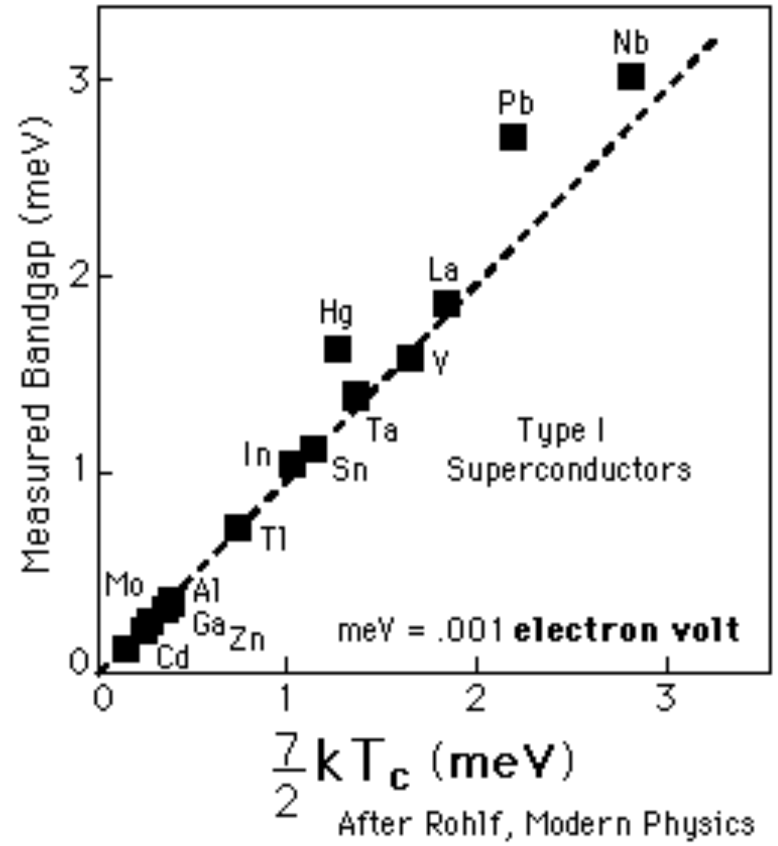
Electrons acting as pairs via lattice interaction? How did they come up with that idea for the BCS theory of superconductivity? The evidence for a small band gap at the Fermi level was a key piece in the puzzle. That evidence comes from the existence of a critical temperature, the existence of a critical magnetic field, and the exponential nature of the heat capacity variation in the Type I superconductors.

The evidence for interaction with the crystal lattice came first from the isotope effect on the critical temperature.

The band gap suggested a phase transition in which there was a kind of condensation, like a Bose-Einstein condensation, but electrons alone cannot condense into the same energy level (Pauli exclusion principle). Yet a drastic change in conductivity demanded a drastic change in electron behavior. Perhaps coupled pairs of electrons with antiparallel spins could act like bosons?

1. One of the first steps toward a theory of superconductivity was the realization that there must be a band gap separating the charge carriers from the state of normal conduction.

- A band gap was implied by the very fact that the resistance is precisely zero. If charge carriers can move through a crystal lattice without interacting at all, it must be because their energies are quantized such that they do not have any available energy levels within reach of the energies of interaction with the lattice.



The measured bandgap in Type I superconductors is one of the pieces of experimental evidence which supports the BCS theory. The BCS theory predicts a bandgap of

$$E_g \approx \frac{7}{2} k T_c$$

where T_c is the critical temperature for the superconductor. The energy gap is related to the coherence length for the superconductor, one of the two characteristic lengths associated with superconductivity.

Boltzmann constant

$k = 0.861 \times 10^{-4}$ eV K^{-1}

2. The critical temperature for superconductivity must be a measure of the band gap, since the material could lose superconductivity if thermal energy could get charge carriers across the gap.
3. The critical temperature was found to depend upon isotopic mass. It certainly would not if the conduction was by free electrons alone. This made it evident that the superconducting transition involved some kind of interaction with the crystal lattice.
4. Single electrons could be eliminated as the charge carriers in superconductivity since with a system of fermions you don't get energy gaps. All available levels up to the Fermi energy fill up.
5. The needed boson behavior was consistent with having coupled pairs of electrons with opposite spins. The isotope effect described above suggested that the coupling mechanism involved the crystal lattice, so this gave rise to the phonon model of coupling envisioned with Cooper pairs.

Quantum Superconducting Effects

Although many properties of superconductors can be described in macroscopic terms such as resistivity, heat capacity, critical temperature, etc., superconductivity is at base a quantum phenomenon and several interesting quantum effects arise.

In 1961, two groups working independently discovered flux quantization - the fact that the magnetic flux through a superconducting ring is an integer multiple of a flux quantum.

The Cooper pairs of a superconductor can tunnel through a thin insulating layer between two superconductors. This is the basis for the Josephson junction which is used in high-speed switching devices.

Flux Quantization

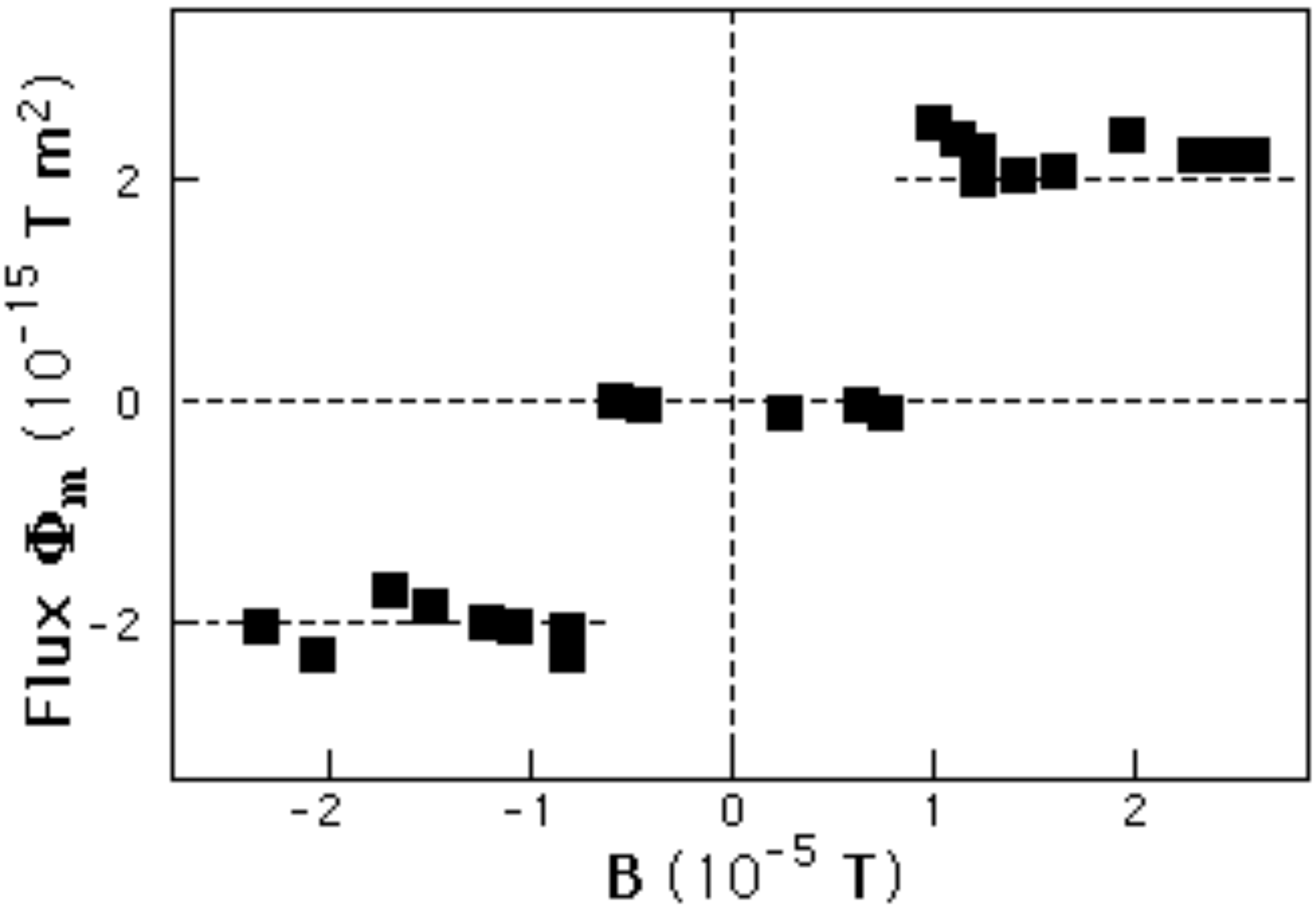
$$\Phi_0 = \frac{h}{2e} = 2.0678 \times 10^{-15}\ \mathrm{T\ m^2}$$

Deaver and Fairbank did experiments with a tiny superconducting cylinder made by electroplating tin on a copper wire. They found magnetic flux quantized in units of

$$\Phi_0 = 2 \times 10^{-15}\ \mathrm{T\ m^2}$$

such that the flux through the cylinder was given by

$$\Phi_m = n\ \Phi_0$$



Quantized magnetic flux in a superconducting ring.
B. S. Deaver and W. M. Fairbank, Phys. Rev. Lett. 7, 43 (1961).

Superconductor Applications

Since 10% to 15% of generated electricity is dissipated in resistive losses in transmission lines, the prospect of zero-loss superconducting transmission lines is appealing. In prototype superconducting transmission lines at Brookhaven National Laboratory, 1000 MW of power can be transported within an enclosure of diameter 40 cm. This amounts to transporting the entire output of a large power plant on one enclosed transmission line. This could be a fairly low voltage DC transmission compared to large transformer banks and multiple high voltage AC transmission lines on towers in the conventional systems. The superconductor used in these prototype applications is usually niobium-titanium, and liquid helium cooling is required.

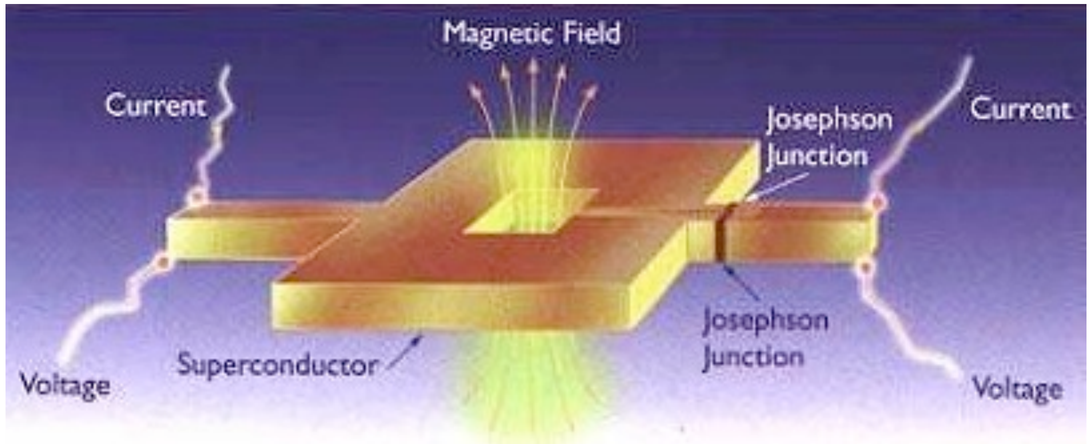
The Holbrook Project on Long Island, the first commercial superconductive power transmission line, uses the high-temperature superconductor BSCCO which only requires liquid nitrogen cooling. The Tres Amigas renewable energy market hub in Clovis, New Mexico, will be a multi-mile, triangular electricity pathway of superconductor electricity pipelines capable of transferring and balancing many gigawatts of power between three U.S. power grids (the Eastern Interconnection, the Western Interconnection and the Texas Interconnection). Unlike traditional powerlines, it will transfer power as DC instead of AC current.

Superconducting Maglev Trains

While it is not practical to lay down superconducting rails, it is possible to construct a superconducting system onboard a train to repel conventional rails below it. The train has to be moving to create the repulsion, but once moving it is supported with very little friction. The German-built Transrapid train in Shanghai, China, transports people 30 km (18.6 miles) to the airport in just 7 minutes 20 seconds, achieving a top speed of 431 km/h (268 mph), averaging 250 km/h (160 mph).

Transrapid 09 at the Emsland Test Facility in Germany

SQUID Magnetometer



The superconducting quantum interference device (SQUID) consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions. The device may be configured as a magnetometer to detect incredibly small magnetic fields -- small enough to measure the magnetic fields in living organisms. Squids have been used to measure the magnetic fields in mouse brains to test whether there might be enough magnetism to attribute their navigational ability to an internal compass.

Threshold for SQUID: 10^{-14} T

Magnetic field of heart: 10^{-10} T

Magnetic field of brain: 10^{-13} T

The great sensitivity of the SQUID devices is associated with measuring changes in magnetic field associated with one flux quantum. One of the discoveries that led to Josephson junctions was that flux is quantized in units

$$\Phi_0 = \frac{h}{2e} = 2.0678 \times 10^{-15}\ \mathrm{T\ m^2}$$

The SQUID magnetometer may be the most sensitive measurement device known to man, according to Berkeley's John Clarke, one of the developers of the concept. He evokes the following images to illustrate its sensitivity:

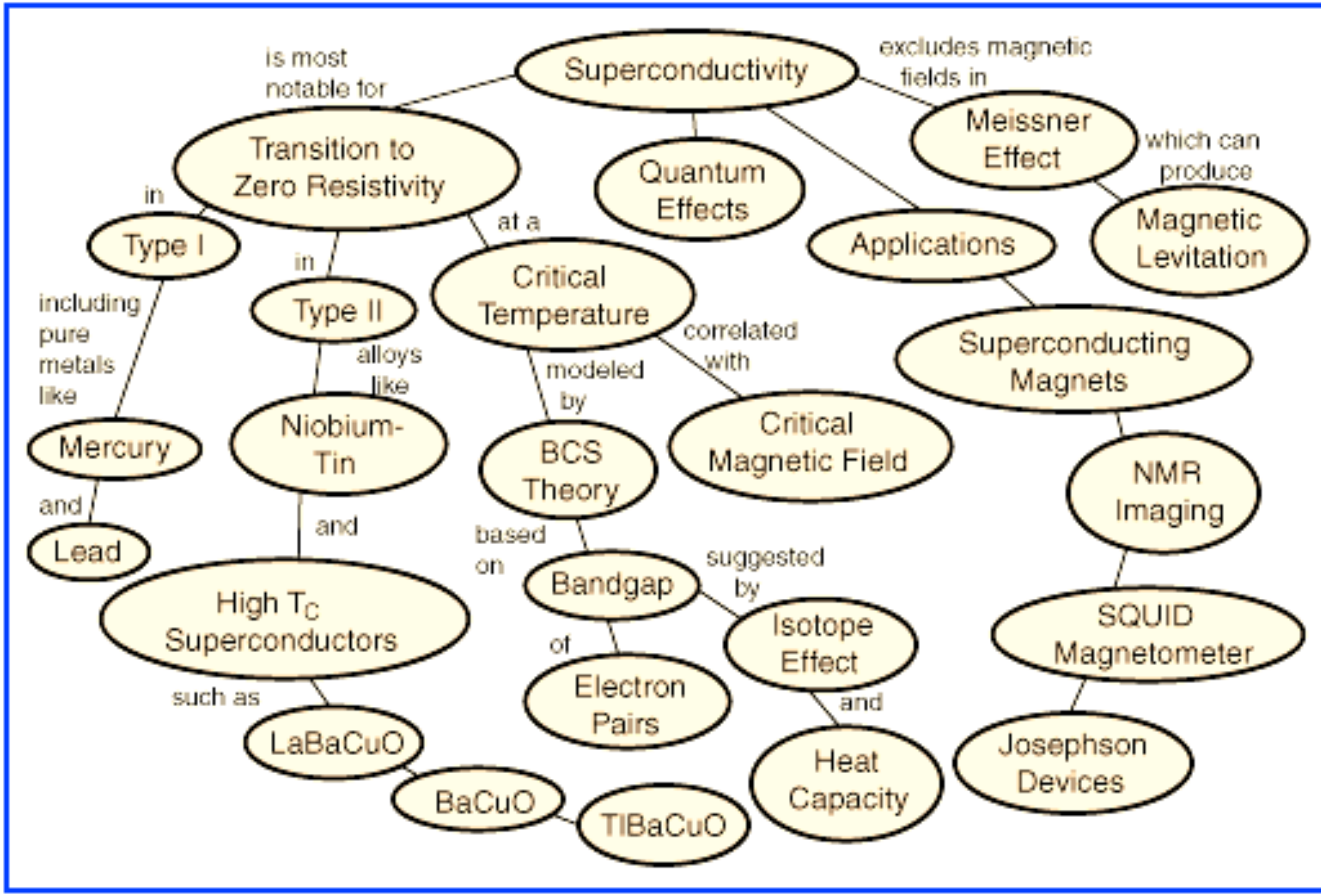
* It can measure magnetic flux on the order of one flux quantum. A flux quantum can be visualized as the magnetic flux of the Earth's magnetic field (0.5 Gauss = 0.5 x 10^{-4} Tesla) through a single human red blood cell (diameter about 7 microns).

* It can measure extremely tiny magnetic fields. The energy associated with the smallest detectable change in a second, about 10^{-32} Joules, is about equivalent to the work required to raise a single electron 1 millimeter in the Earth's gravitational field!

The sensitivity of the basic SQUID can be increased by attaching it to a flat coil of superconducting wire, such as niobium. Called a "flux transformer", this increases the current induced in the junction and permits the detection of magnetic fields as small as 10^{-15} Tesla or one femto-Tesla. This is a resolution of some 10^{-11} times the Earth's magnetic field. By comparison, the auroral displays in Earth's polar region produce magnetic field fluctuations on the order of 1% of the Earth's field.

Superconductors in MRI

Superconducting magnets find application in magnetic resonance imaging (MRI) of the human body. Besides requiring strong magnetic fields on the order of a Tesla, magnetic resonance imaging requires extremely uniform fields across the subject and extreme stability over time. Maintaining the magnet coils in the superconducting state helps to achieve parts-per-million spacial uniformity over a space large enough to hold a person, and ppm/hour stability with time.



http://hyperphysics.phy-astr.gsu.edu/hbase/solids/supcon.html#c1