

Definition of Superconductivity

Superconductivity is a phenomenon occurring in certain materials at low temperatures, characterised by the complete absence of electrical resistance and the damping of the interior magnetic field (the Meissner effect.)

Superconductivity occurs in a wide variety of materials, including simple elements like tin and aluminium, various metallic alloys, some heavily-doped semiconductors, and certain ceramic compounds containing planes of copper and oxygen atoms. The latter class of compounds, known as the cuprates, are high-temperature superconductors. Superconductivity does not occur in noble metals like gold and silver, nor in ferromagnetic metals.

In conventional superconductors, superconductivity is caused by a force of attraction between certain conduction electrons arising from the exchange of phonons, which causes the conduction electrons to exhibit a superfluid phase composed of correlated *pairs* of electrons. There also exists a class of materials, known as unconventional superconductors, that exhibit superconductivity but whose physical properties contradict the theory of conventional superconductors. In particular, the so-called high-temperature superconductors superconduct at temperatures much higher than should be possible according to the conventional theory (though still far below room temperature.) There is currently no complete theory of high-temperature superconductivity.

Contents

- 1 Elementary properties of superconductors
 - 1.1 Zero electrical resistance
 - 1.2 Superconducting phase transition
 - 1.3 Meissner effect
- 2 Theories of superconductivity
- 3 History of superconductivity
- 4 Technological applications of superconductivity
- 5 Superconductors in science fiction
- 6 References
 - 6.1 Selected papers
 - 6.2 External links
- 7 See also

Elementary properties of superconductors

Most of the physical properties of superconductors vary from material to material, such as the heat capacity and the critical temperature at which superconductivity is destroyed. On the other hand, there is a class of properties that are independent of the underlying material. For instance, all superconductors have *exactly* zero resistivity to low applied currents when there is no magnetic field present. The existence of these "universal" properties imply that superconductivity is a thermodynamic phase, and thus possess certain distinguishing properties which are largely independent of microscopic details.

Zero electrical resistance

Suppose we were to attempt to measure the electrical resistance of a piece of superconductor. The simplest method is to place the sample in an electrical circuit, in series with a voltage (potential difference) source V (such as a battery), and measure the resulting current. If we carefully account for the resistance R of the remaining circuit elements (such as the leads connecting the sample to the rest of the circuit, and the source's internal resistance), we would find that the current is simply V/R . According to Ohm's law, this means that the resistance of the superconducting sample is zero. Superconductors are also quite willing to maintain a current with no applied voltage whatsoever, a property exploited in the coils of MRI machines, among others.

In a normal conductor, an electrical current may be visualized as a fluid of electrons moving across a heavy ionic lattice.

The electrons are constantly colliding with the ions in the lattice, and during each collision some of the energy carried by the current is absorbed by the lattice and converted into heat (which is essentially the vibrational kinetic energy of the lattice ions.) As a result, the energy carried by the current is constantly being dissipated. This is the phenomenon of electrical resistance.

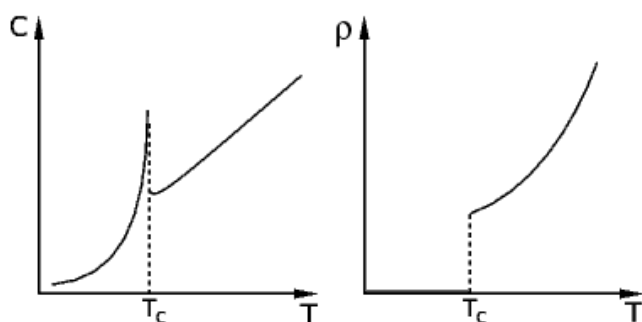
The situation is different in a superconductor. In a conventional superconductor, the electronic fluid cannot be resolved into individual electrons, instead consisting of bound *pairs* of electrons known as Cooper pairs. This pairing is caused by an attractive force between electrons from the exchange of phonons. Due to quantum mechanics, the energy spectrum of this Cooper pair fluid possesses an *energy gap*, meaning there is a minimum amount of energy ΔE that must be supplied in order to excite the fluid. Therefore, if ΔE is larger than the thermal energy of the lattice (given by kT , where k is Boltzmann's constant and T is the temperature), the fluid will not be scattered by the lattice. The Cooper pair fluid is thus a superfluid, meaning it can flow without energy dissipation. Experiments have in fact demonstrated that currents in superconducting rings persist for years without any measurable degradation.

(Note: actually, in a class of superconductors known as type II superconductors, a small amount of resistivity appears when a strong magnetic field and electrical current are applied. This is due to the motion of vortices in the electronic superfluid, which dissipates some of the energy carried by the current. If the current is sufficiently small, the vortices are stationary, and the resistivity vanishes.)

Superconducting phase transition

In superconducting materials, the characteristics of superconductivity appear when the temperature T is lowered below a **critical temperature** T_c . The value of this critical temperature varies from material to material. Conventional superconductors usually have critical temperatures ranging from less than 1K to around 20K. Solid mercury, for example, has a critical temperature of 4.2K. As of 2001, the highest critical temperature found for a conventional superconductor is 39K for magnesium diboride (MgB_2), although this material displays enough exotic properties that there is doubt about classifying it as a "conventional" superconductor. Cuprate superconductors can have much higher critical temperatures: $\text{YBa}_2\text{Cu}_3\text{O}_7$, one of the first cuprate superconductors to be discovered, has a critical temperature of 92K, and mercury-based cuprates have been found with critical temperatures in excess of 130K. The explanation for these high critical temperatures remains unknown. (Electron pairing due to phonon exchanges explains superconductivity in conventional superconductors, while it does not explain superconductivity in the newer superconductors that have a very high T_c)

The onset of superconductivity is accompanied by abrupt changes in various physical properties, which is the hallmark of a phase transition. For example, the electronic heat capacity is proportional to the temperature in the normal (non-superconducting) regime. At the superconducting transition, it suffers a discontinuous jump and thereafter ceases to be linear. At low temperatures, it varies instead as $e^{-\alpha/T}$ for some constant α . (This exponential behavior is one of the pieces of evidence for the existence of the energy gap.)



Behavior of heat capacity (C) and resistivity (ρ) at the superconducting phase transition

The order of the superconducting phase transition is still a matter of debate. It had long been thought that the transition is second-order, meaning there is no latent heat. However, recent calculations have suggested that it may actually be weakly first-order due to the effect of long-range fluctuations in the electromagnetic field.

Meissner effect

When a superconductor is placed in a weak external magnetic field \mathbf{H} , the field penetrates for only a short distance λ , called the **penetration depth**, after which it decays rapidly to zero. This is called the **Meissner effect**. For most superconductors, the penetration depth is on the order of a hundred nm.

The Meissner effect is sometimes confused with the "perfect diamagnetism" one would expect in a perfect electrical conductor: according to Lenz's law, when a *changing* magnetic field is applied to a conductor, it will induce an electrical current in the conductor that creates an opposing magnetic field. In a perfect conductor, an arbitrarily large current can be induced, and the resulting magnetic field exactly cancels the applied field.

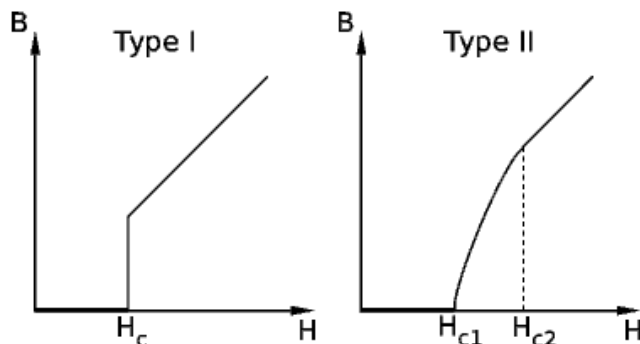
The Meissner effect is distinct from perfect diamagnetism because a superconductor expels *all* magnetic fields, not just those that are changing. Suppose we have a material in its normal state, containing a constant internal magnetic field. When the material is cooled below the critical temperature, we would observe the abrupt expulsion of the internal magnetic field, which we would not expect based on Lenz's law. A conductor in a static field, such as the dome of a Van de Graff generator, will have a field within itself, even if there is no net charge in the interior.

The Meissner effect was explained by London and London, who showed that the electromagnetic free energy in a superconductor is minimized provided

$$\nabla^2 \mathbf{H} = -\lambda^{-2} \mathbf{H}$$

where \mathbf{H} is the magnetic field and λ is the penetration depth. This equation, which is known as the London equation, predicts that the magnetic field in a superconductor decays exponentially from whatever value it possesses at the surface.

The Meissner effect breaks down when the applied magnetic field is too large. Superconductors can be divided into two classes according to how this breakdown occurs. In **Type I** superconductors, superconductivity is abruptly destroyed when the strength of the applied field rises above a critical value H_c . Depending on the geometry of the sample, one may obtain an **intermediate state** consisting of regions of normal material carrying a magnetic field mixed with regions of superconducting material containing no field. In **Type II** superconductors, raising the applied field past a critical value H_{c1} leads to a **mixed state** in which an increasing amount of magnetic flux penetrates the material, but there remains no resistance to the flow of electrical current as long as the current is not too large. At a second critical field strength H_{c2} , superconductivity is destroyed. The mixed state is actually caused by vortices in the electronic superfluid, sometimes called "fluxons" because the flux carried by these vortices is quantized. Most pure elemental superconductors (except niobium) are Type I, while almost all impure and compound superconductors are Type II.



Variation of internal magnetic field (B) with applied external magnetic field (H) for Type I and Type II superconductors

Theories of superconductivity

Since the discovery of superconductivity, great efforts have been devoted to finding out how and why it works. During the 1950s, theoretical condensed matter physicists arrived at a solid understanding of "conventional" superconductivity, through a pair of remarkable and important theories: the phenomenological Ginzburg-Landau theory (1950) and the microscopic BCS theory (1957).

History of superconductivity

Superconductivity was discovered in 1911 by Onnes, who was studying the resistivity of solid mercury at cryogenic temperatures using the recently-discovered liquid helium as a refrigerant. At the temperature of 4.2K, he observed that the resistivity abruptly disappeared. For this discovery, he was awarded the Nobel Prize in Physics in 1913.

In subsequent decades, superconductivity was found in several other materials. In 1913, lead was found to superconduct at 7K, and in 1941 niobium nitride was found to superconduct at 16K.

The next important step in understanding superconductivity occurred in 1933, when Meissner and Ochsenfeld discovered that superconductors expelled applied magnetic fields, a phenomenon which has come to be known as the Meissner effect. In 1935, F. and H. London showed that the Meissner effect was a consequence of the minimization of the electromagnetic free energy carried by superconducting current.

In 1950, the phenomenological Ginzburg-Landau theory of superconductivity was devised by Landau and Ginzburg. This theory, which combined Landau's theory of second-order phase transitions with a Schrödinger-like wave equation, had great success in explaining the macroscopic properties of superconductors. In particular, Abrikosov showed that Ginzburg-Landau theory predicts the division of superconductors into the two categories now referred to as Type I and Type II. Abrikosov and Ginzburg were awarded the 2003 Nobel Prize for their work (Landau having died in 1968.)

Also in 1950, Maxwell and Reynolds *et. al.* found that the critical temperature of a superconductor depends on the isotopic mass of the constituent element. This important discovery pointed to the electron-phonon interaction as the microscopic mechanism responsible for superconductivity.

The complete microscopic theory of superconductivity was finally proposed in 1957 by Bardeen, Cooper, and Schrieffer. This BCS theory explained the superconducting current as a superfluid of Cooper pairs, pairs of electrons interacting through the exchange of phonons. For this work, the authors were awarded the Nobel Prize in 1972.

The BCS theory was set on a firmer footing in 1958, when Bogoliubov showed that the BCS wavefunction, which had originally been derived from a variational argument, could be obtained using a canonical transformation of the electronic Hamiltonian. In 1959, Gor'kov showed that the BCS theory reduced to the Ginzburg-Landau theory close to the critical temperature.

In 1962, the first commercial superconducting wire, a niobium-titanium alloy, was developed by researchers at Westinghouse. In the same year, Josephson made the important theoretical prediction that a supercurrent can flow between two pieces of superconductor separated by a thin layer of insulator. This phenomenon, now called the Josephson effect, is exploited by superconducting devices such as SQUIDs. It is used in the most accurate available measurements of the magnetic flux quantum h/e , and thus (coupled with the quantum Hall resistivity) for Planck's constant h . Josephson was awarded the Nobel Prize for this work in 1973.

In 1986, Bednorz and Mueller discovered superconductivity in a lanthanum-based cuprate perovskite material, which had a transition temperature of 35K (Nobel Prize in Physics, 1987). It was shortly found that replacing the lanthanum with yttrium, i.e. making YBCO, raised the critical temperature to 92K, which was important because liquid nitrogen could then be used as a refrigerant (at atmospheric pressure, the boiling point of nitrogen is 77K.) This is important commercially because liquid nitrogen can be produced cheaply on-site with no raw materials, and is not prone to some of the problems (solid air plugs, etc) of helium in piping. Many other cuprate superconductors have since been discovered, and the theory of superconductivity in these materials is one of the major outstanding challenges of theoretical condensed matter physics.

Technological applications of superconductivity

Some technological innovations benefiting from the discovery of superconductivity include sensitive magnetometers based on SQUIDs, digital circuits (e.g. based on the RSFQ logic), Magnetic Resonance Imaging, beam-steering magnets in particle accelerators, electric power transmission cables, and microwave filters (e.g., for mobile phone base stations). Promising future industrial and commercial applications include transformers, power storage, propulsion systems for vehicles such as ships and spacecraft, electric motors, super fast computer circuits, and magnetic levitation devices. Most applications employ the well-understood conventional superconductors, but it is expected that high-temperature superconductors will soon become more cost-effective in many cases.

Superconductors in science fiction

Superconductivity has long been a staple of science fiction. An early mention of the phenomenon occurred in Robert Heinlein's novel *Beyond This Horizon* (1942). Notably, the use of a fictional room temperature superconductor was a major plot point in the *Ringworld* novels by Larry Niven, first published in 1970.

Superconductivity is a popular device in science fiction due to the simplicity of the underlying concept - zero electrical resistance - and the rich technological possibilities. For example, superconducting magnets could be used to generate the powerful magnetic fields used by Bussard ramjets, a type of spacecraft commonly encountered in science fiction. The most troublesome property of real superconductors, the need for cryogenic cooling, is often circumvented by postulating the existence of room temperature superconductors. Many stories attribute additional properties to their hypothetical superconductors, ranging from infinite heat conductivity in Niven's novels (real superconductors conduct heat poorly, though liquid helium has immense heat conductivity) to teleportation in the *Stargate* movie and TV series.

References

Selected papers

- H.K. Onnes, *Commun. Phys. Lab.* **12**, 120 (1911)
- W. Meissner and R. Oschenfeld, *Naturwiss.* **21**, 787 (1933)
- F. London and H. London, *Proc. R. Soc. London* **A149**, 71 (1935)
- V.L. Ginzburg and L.D. Landau, *Zh. Eksp. Teor. Fiz.* **20**, 1064 (1950)
- E.Maxwell, *Phys. Rev.* **78**, 477 (1950)
- C.A. Reynolds et. al., *Phys. Rev.* **78**, 487 (1950)
- J. Bardeen, L.N. Cooper, and J.R. Schrieffer, *Phys. Rev.* **108**, 1175 (1957)
- N.N. Bogoliubov, *Zh. Eksp. Teor. Fiz.* **34**, 58 (1958)
- L.P. Gor'kov, *Zh. Eksp. Teor. Fiz.* **36**, 1364 (1959)
- B.D. Josephson, *Phys. Lett.* **1**, 251 (1962)
- J.G. Bednorz and K.A. Mueller, *Z. Phys.* **B64**, 189 (1986)

External links

- US, EREN: superconductivity (<http://www.eren.doe.gov/superconductivity/>)
- superconductors.org (<http://www.superconductors.org/>)

See also

- Timeline of low-temperature technology
- Homes's law

Categories: Electromagnetism | Condensed matter physics

Encyclopedia Index: A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

[Superconductor Newsletter](#)
Exclusive info on
superconductivity technology,
business and markets

[Foundations of Physics](#)
Leading research on the
Fundamental Theories of Physics.

[Superconductor Substrates](#)
LaAlO₃, SrTiO₃, MgO, Sapphire
Bi-Crystal Substrates at low cost

[Master Bond Inc.](#)
Industrial Adhesives That Meet
Your Needs

All text is available under the terms of the GNU Free Documentation License. [Privacy Policy](#) :: [Terms of Use](#)
:: [Contact Us](#) :: [About Us](#)

This article is licensed under the GNU Free Documentation License. It uses material from the Wikipedia article "Superconductivity". The list of authors can be found here.