The Meissner Effect

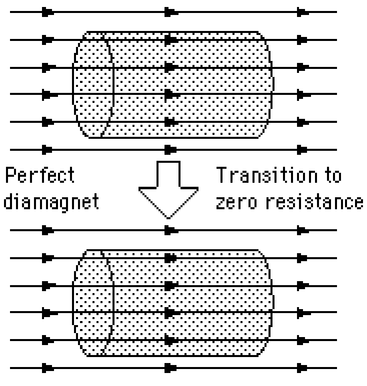
When a material makes the transition from the normal to superconducting state, it actively excludes magnetic fields from its interior; this is called the Meissner effect.

This constraint to zero magnetic field inside a superconductor is distinct from the perfect diamagnetism which would arise from its zero electrical resistance. Zero resistance would imply that if you tried to magnetize a superconductor, current loops would be generated to exactly cancel the imposed field (Lenz's law). But if the material already had a steady magnetic field through it when it was cooled trough the superconducting transition, the magnetic field would be expected to remain. If there were no change in the applied magnetic field, there would be no generated voltage (Faraday's law) to drive currents, even in a perfect conductor. Hence the active exclusion of magnetic field must be considered to be an effect distinct from just zero resistance. A mixed state Meissner effect occurs with Type II materials.

One of the theoretical explanations of the Meissner effect comes from the London equation. It shows that the magnetic field decays exponentially inside the superconductor over a distance of 20-40 nm. It is described in terms of a parameter called the London penetration depth.

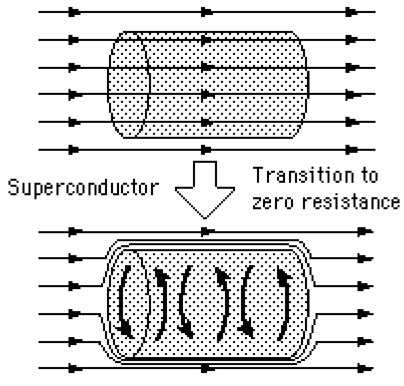
Perfect Diamagnet

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

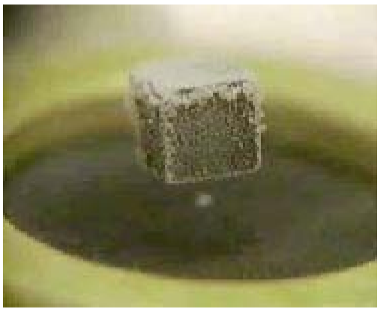
Remarkably, the magnetic behavior of a superconductor is distinct from perfect diamagnetism. It will actively exclude any magnetic field present when it makes the phase change to the superconducting state.

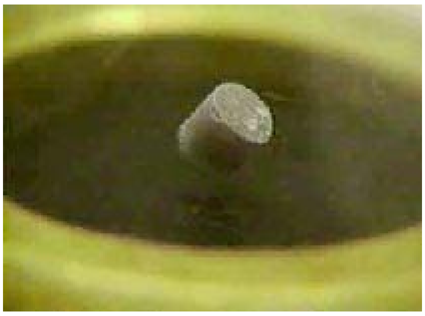


Magnetic Levitation

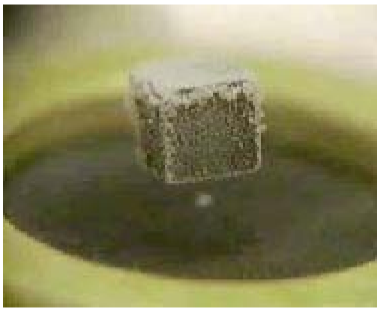
Magnetic fields are actively excluded from superconductors (Meissner effect). If a small magnet is brought near a superconductor, it will be repelled becaused induced supercurrents will produce mirror images of each pole. If a small permanent magnet is placed above a superconductor, it can be levitated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

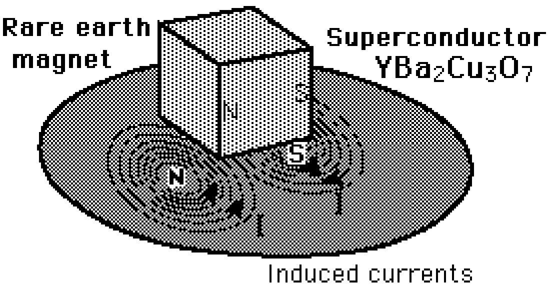
By tapping with a sharp instrument, the suspended magnet can be caused to oscillate or rotate. This motion is found to be damped, and will come to rest in a few seconds.





Levitation Currents





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.

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.

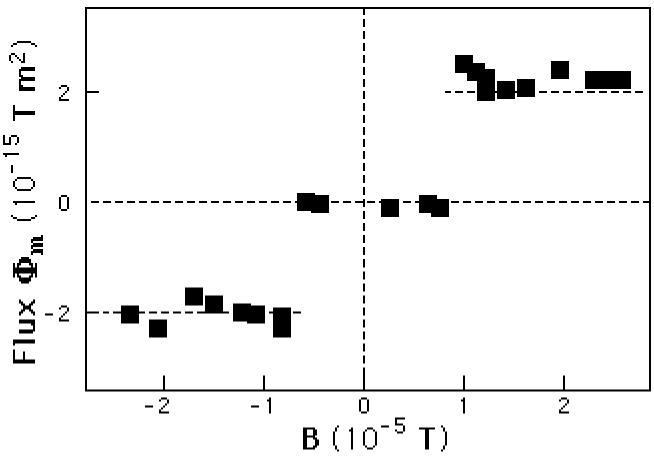
Flux Quantization

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).

Type I Superconductors

The 27 pure metals listed in the table below are called Type I superconductors. The identifying characteristics are zero electrical resistivity below a critical temperature, zero internal magnetic field (Meissner effect), and a critical magnetic field above which superconductivity ceases.

The superconductivity in Type I superconductors is modeled well by the BCS theory which relies upon electron pairs coupled by lattice vibration interactions. Remarkably, the best conductors at room temperature (gold, silver, and copper) do not become superconducting at all. They have the smallest lattice vibrations, so their behavior correlates well with the BCS Theory.

While instructive for understanding superconductivity, the Type I superconductors have been of limited practical usefulness because the critical magnetic fields are so small and the superconducting state disappears suddenly at that temperature. Type I superconductors are sometimes called "soft" superconductors while the Type II are "hard", maintaining the superconducting state to higher temperatures and magnetic fields.

Mat.	Tc (K)
Rh	0
W	0.015
Be**	0.026
Ir	0.1
Lu	0.1
Hf	0.1
Ru	0.5
Os	0.7
Mo	0.92
Zr	0.546
Cd	0.56
U	0.2
Ti	0.39
Zn	0.85
Ga	1.083

Mat.	Tc (K)
Gd*	1.1
Al	1.2
Pa	1.4
Th	1.4
Re	1.4
Tl	2.39
In	3.408
Sn	3.722
Hg	4.153
Ta	4.47
La	6.00
Pb	7.193

*Gd at T_c=1.1 is questionable. Source is Rohlf, Ch 15, but this may be a misprint. Ga has T_c about 1.1, so Ga value may have been attributed to Gd.

**"Superconductivity of Hexagonal Beryllium'" R.L. Falge Jr., Physics Letters A 24 1967.

Note also the three metals at right which were formerly included as Type I superconductors in the above table, but have been shown to exhibit Type II properties.

Mat.	Tc
V	5.38
Tc	7.77
Nb	9.46

Type II Superconductors

Superconductors made from alloys are called Type II superconductors. Besides being mechanically harder than Type I superconductors, they exhibit much higher critical magnetic fields. Type II superconductors such as niobium-titanium (NbTi) are used in the construction of high field superconducting magnets.

Type-II superconductors usually exist in a mixed state of normal and superconducting regions. This is sometimes called a vortex state, because vortices of superconducting currents surround filaments or cores of normal material.

Material	Transition Temp (K)	Critical Field (T)
NbTi	10	15
PbMoS	14.4	6.0
V_3Ga	14.8	2.1
NbN	15.7	1.5
V_3Si	16.9	2.35
Nb_3Sn	18.0	24.5
Nb_3Al	18.7	32.4
$Nb_3(AlGe)$	20.7	44
Nb_3Ge	23.2	38

From Blatt, Modern Physics

Magnesium Diboride

In March 2001, Jun Akimitsu and colleagues at Aoyama-Gakuin University in Tokyo, Japan reported a superconducting transition temperature of 39 Kelvin for magnesium diboride. This has generated a great deal of excitement not only because this is the highest transition temperature yet observed for a type-II superconductor, but also because the materials used are quite common.

There will be a great deal of interest in whether the material can be used to form wires. If its mechanical properties can be managed, it could contribute significantly to making superconducting magnets. Sergey L. Bud'ko and colleagues at Iowa State University have formed wires from the material. They observed the isotope effect in this superconductor, suggesting that it follows the behavior of other conventional superconductors. The isotope effect is a signature of interaction with the crystal lattice via phonons, and is an indication that the superconductor may act according to the BCS theory of superconductivity.

All of this is preliminary information. Part of it was drawn from:
"Run-of-the-mill compound becomes superstar" by P. Weiss, Science News 159, p134 (Mar 3, 2001)

Superconducting Plutonium

The plutonium compound $PuCoGa_5$ has been found to be superconducting with a critical temperature of about 18 K. Gregory Stewart of the University of Florida and John Sarrao and colleagues at the Los Alamos National Laboratory reported this unexpected superconductor in the journal Nature.