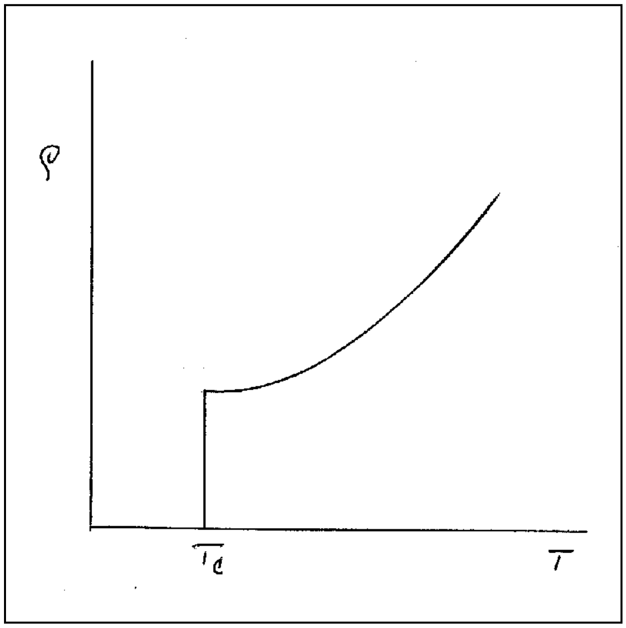
SUPERCONDUCTIVITY

property of complete disappearance of electrical resistance in solids when they are cooled below a characteristictemperature.Thistemperatureiscalled transition temperature or critical temperature.



Superconductive state of mercury (T_C=4.15 K) was discovered by the Dutch physicist Heike Kamerlingh Onnes in 1911, several years after the discovery of liquid helium.

Classicalelementalsuperconductors

Element	Transitiontemperature,K
Zinc	0.88
Aluminum	1.20
Indium	3.41
Tin	3.72
Mercury	4.15
Lead	7.19

Until1983recordT_c=23.3K wasthatofNb_3Gealloy.

Progressin$T_c$ofsuperconductormaterialswithtime

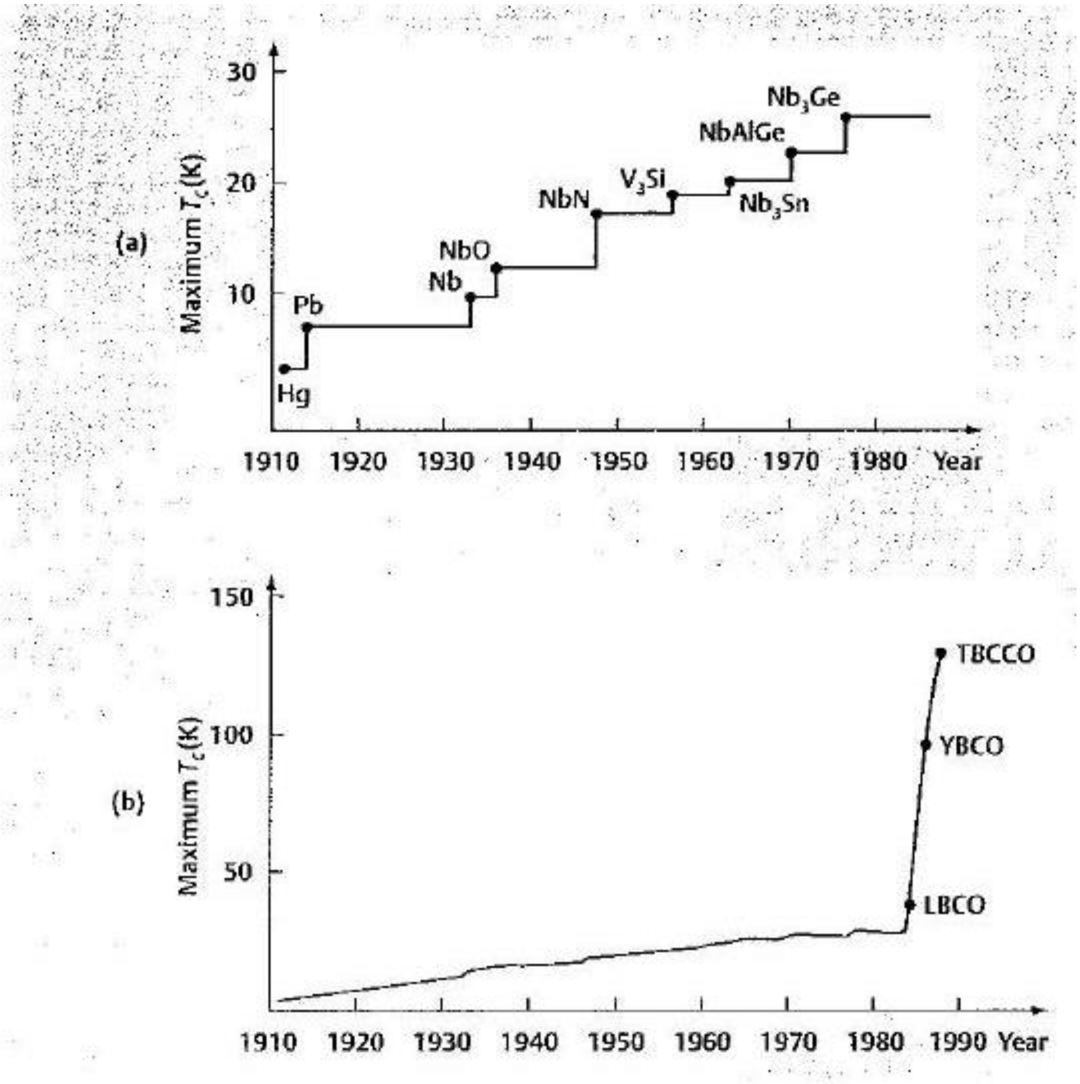


Figure 9.22 (a) Graph showing the historical rise of the maximum known critical temperature up to 1985. (b) Extended to include high-temperature superconductors.

Hightemperaturesuperconductorsdiscoveredin 1986: T_c=80-93 K, parent structure $YBa_2Cu_3O_7$.

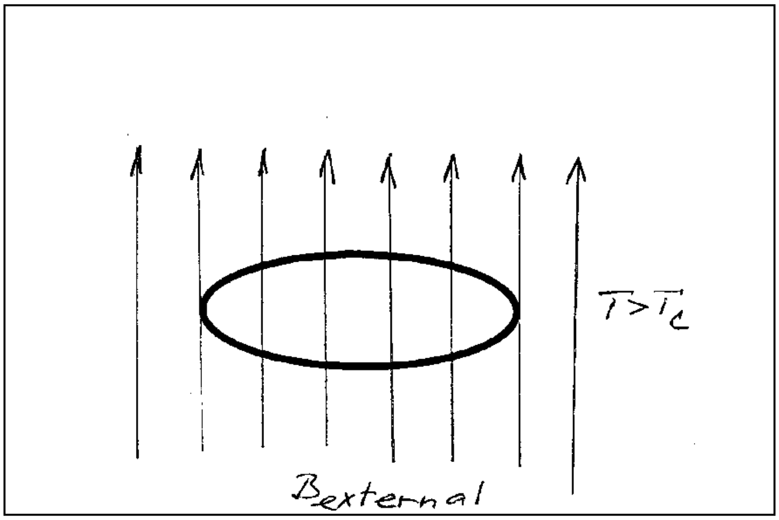
At present the record transition temperature (TBCCO) is now at T_C= 134 K.

Effectoftrappedmagneticflux

Consider a ring made out of superconductive material.

Performthefollowingthoughtexperiment:

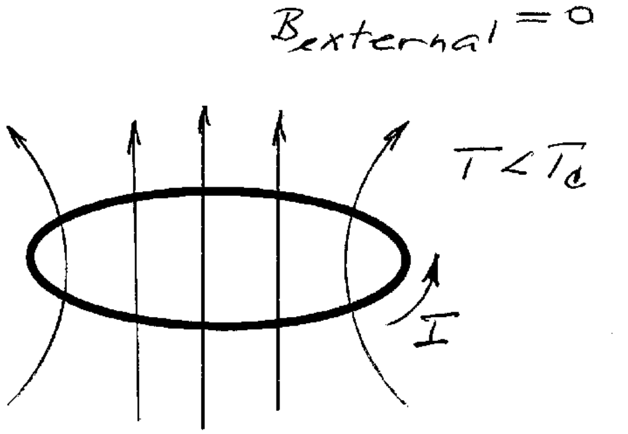
1. At $T>T_c$ the material is normal state. When the external magnetic field is turned on, it penetrates through the ring.



2. ReducethetemperaturesothatT<T_c.

3. Removetheexternalmagneticfield.

4. You discover that the magnetic field that was penetrating through the opening of the ring magnetic field remains there. The magnetic flux remains trapped in the ring opening.



This effect can be explained in terms of Faraday's law of induction

$$\oint \vec{E}\cdot d\vec{l} = -\frac{d\Phi}{dt}$$

$$\oint \vec{E}.d\vec{l} = -\frac{d\Phi}{dt}$$

where E is the electric filed along the closed loop, Φ is the magnetic flux through the opening of the ring.

Before the external magnetic field was turned off there was a magnetic flux Φ=B.(area) through the ring.

Below T_c the resistivity of superconductor becomes equal to zero and therefore at $T<T_c$ the electric field inside the superconductor must be and is zero as well. In view of this

$$\oint E.dl = 0$$

and therefore, the right side of Faraday's equation

$$\frac{d\Phi}{dt} = 0$$

which means that

$$\Phi = B(area) = const$$

The magnetic flux Φ through the ring must remain constant. For this reason the magnetic flux remains trapped in the opening of the ring after the external magnetic field has been turned off.

There is no magic involved. The trapped magnetic field passing through the ring is due to the current induced in the ring when the external magnetic field was turned off.

Theinducedcurrentiscalledthepersistentcurrent.

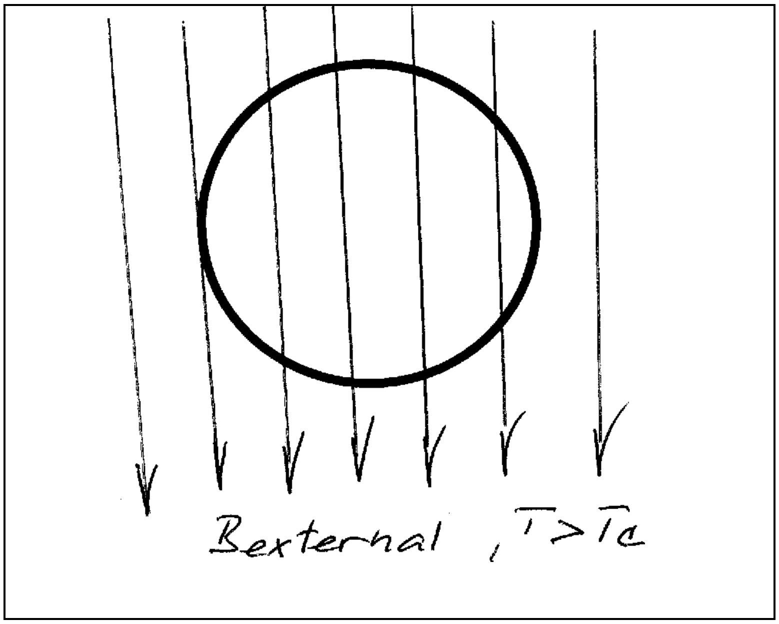
The current persists, it does not decay because the resistance of the ring is zero. Actually no decrease of current was observed over the period of three years! Theoretically,therelaxationtimeofcurrentcarriersin the superconductor is greater than the age of universe.

Meissnereffect

expulsionof magnetic fieldfrom theinterior of the superconductor

Thoughtexperiment

Consider a sphere made out of superconductive material. At $T>T_c$ the material is in normal state. When external magnetic field is turned on, the external magnetic field penetrates through the material.

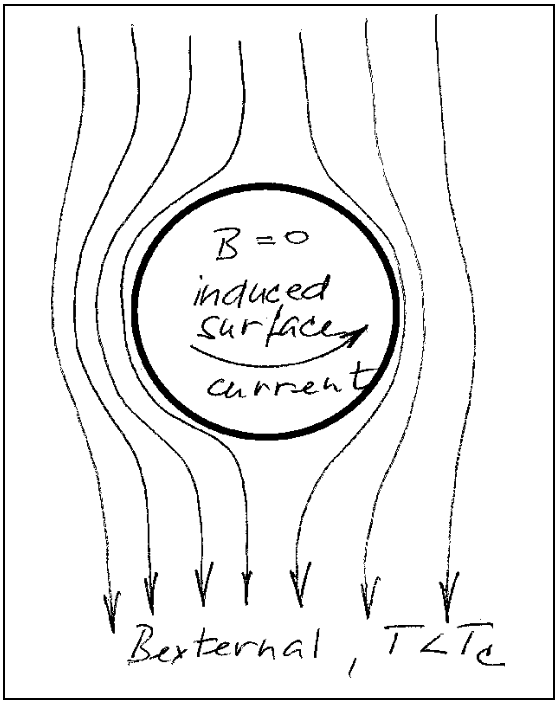


OnthebasisofFaraday'slaw,

$$\oint \vec{E}.\vec{dl} = -\frac{d\Phi}{dt}$$

onewouldexpectthatat$T<T_c$themagneticfield would remain trapped in the material after the external field has been turned off.

The trapping of magnetic field does not happen (the absence of magnetic field inside the superconductor is the Meissner effect).
Thisiswhathappens:



The magnetic field is expelled from the interior of the superconductor, inside the superconductor B=0.

Superconductor expels magnetic field from the interior by setting up electric current at the surface. The surface current creates magnetic field that exactly cancels the external magnetic field!

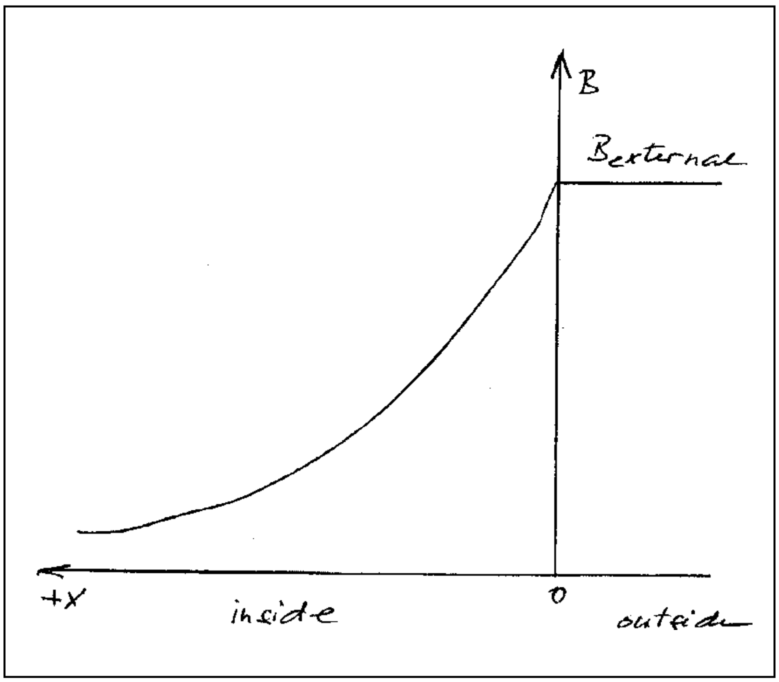
This electric current at the surface of the superconductor appears at $T<T_c$ in order that B=0 inside the superconductor.

Penetration of magnetic field below the surface of superconductors

Thesurfacecurrentisdistributedinthesurfacelayer,
the layer carrying the electric current has a finite thickness, and because of this, the external magnetic field partially penetrates into the interior of the superconductor,

$$B(x) = B_{external} \exp\left(-\frac{x}{\lambda}\right)$$

λ=penetrationdistanceattemperatureT;



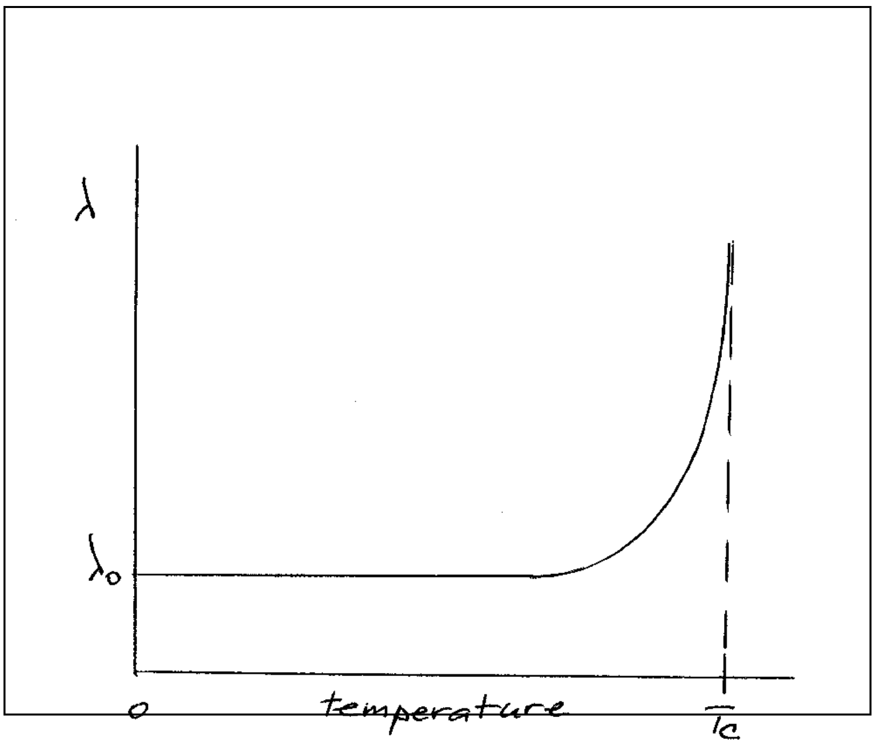
Temperaturedependenceofpenetrationdistance

λ=penetrationdistanceattemperatureT;

λ_0=penetrationdistanceattemperatureT=0.

$$\lambda = \frac{\lambda_0}{\sqrt{1 - \left(\frac{T}{T_C}\right)^4}}$$

λ_0=30-130nm,dependingonthesuperconductor material



Themagneticpropertiesof superconductors

In addition to the loss of resistance, superconductors prevent external magnetic field from penetrating the interior of the superconductor. This expulsion of external magnetic fields takes place for magnetic fields that are less than the critical field. Magnetic field greater than B_C destroys the superconductive state.

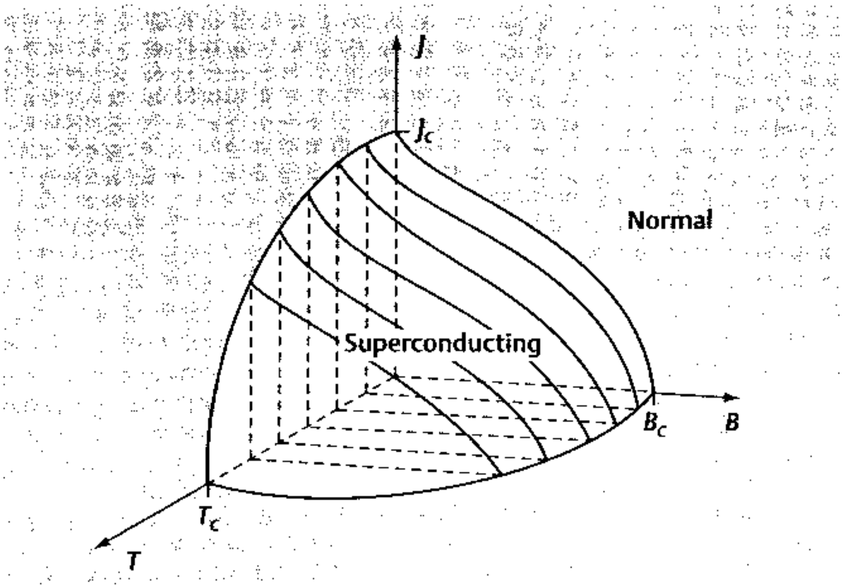


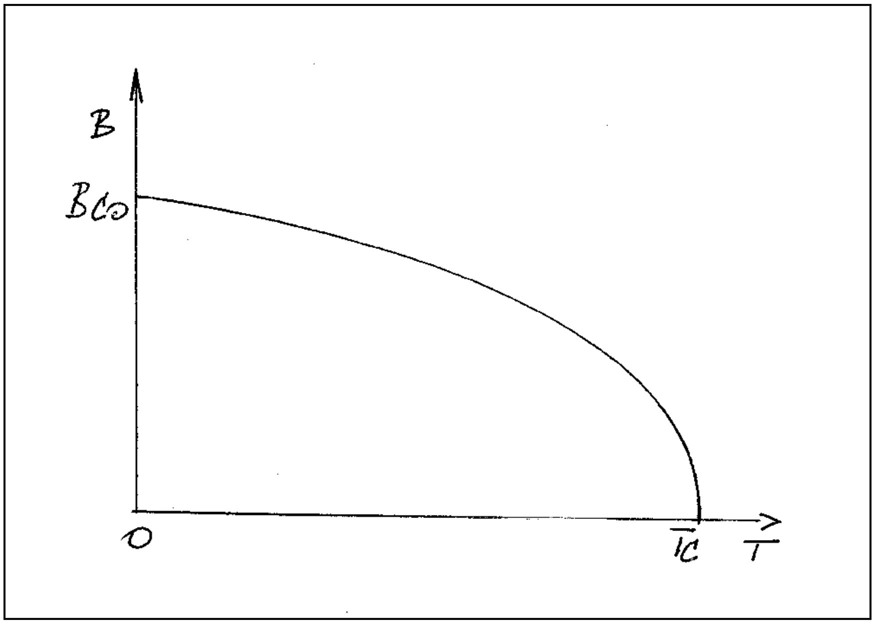
Figure 9.4 The ability of a material to superconduct depends on three factors: the temperature, T, the magnetic field strength, B, and the current density J. T_c is the critical temperature in the absence of an external magnetic field and with no current flowing in the sample, B_c is the critical magnetic field strength with no current flowing at $T = 0$ K, and J_c is the critical current density at $T = 0$ K with no external magnetic field. The critical surface shown in the figure separates the superconducting and normal states.

Criticalmagneticfield

The critical magnetic field depends upon the temperature,

$$B_C(T) = B_{C0}\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

B_{C0}=criticalmagneticfieldatT=0.



Relationship between resistivity(a), magnetic field inside the superconductive material (b) and magnetization of superconductor as a function of external magnetic field

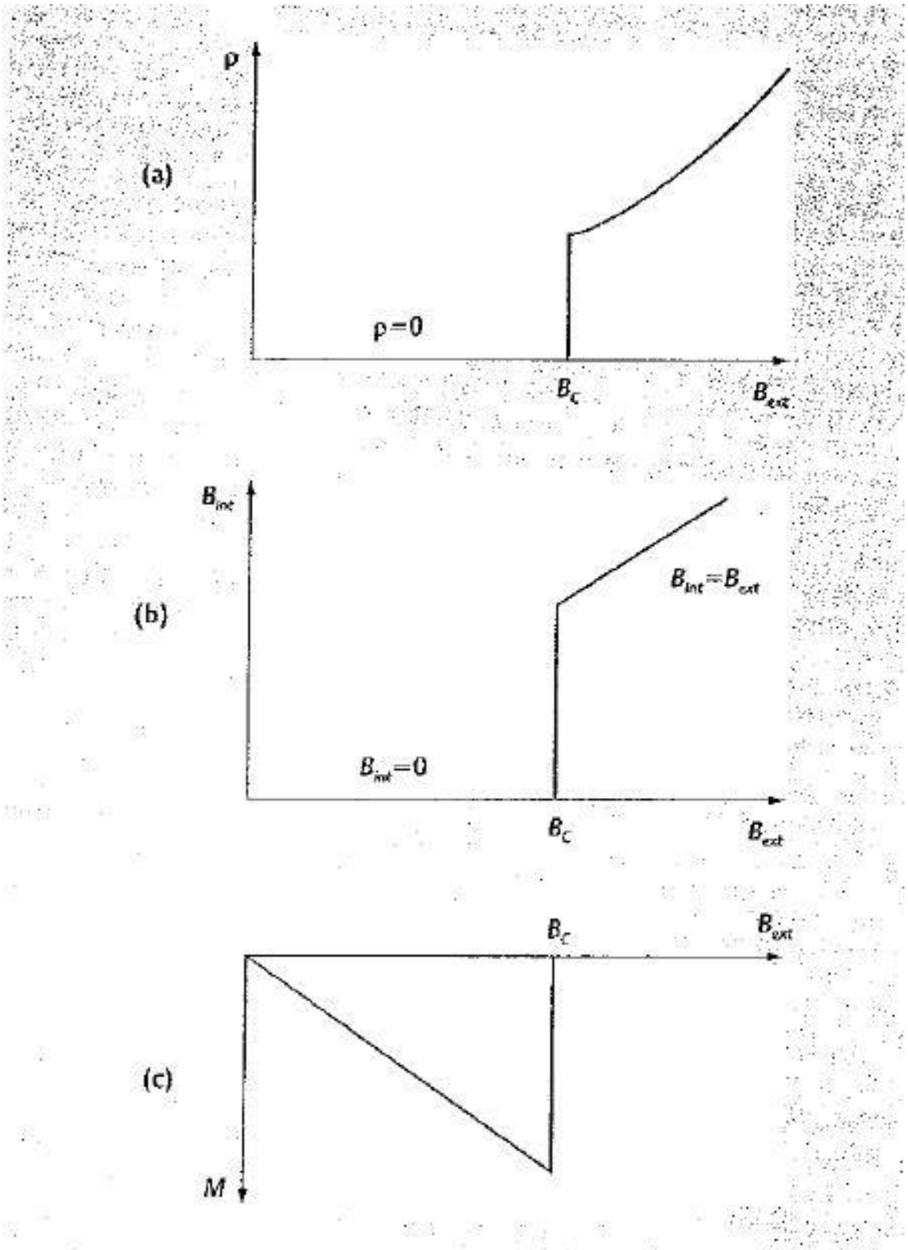


Figure 9.8 Properties of a type I superconductor showing (a) the resistivity ρ, (b) the internal magnetic field strength B_{int} and (c) the magnetization M as a function of the external magnetic field strength B_{ext}.

Criticalcurrent

Superconductivestateisdestroyedbymagneticfield.

Consider a straight wire. Since electric current in the wire creates magnetic field

$$B = \frac{\mu_0 I}{2\pi r}$$

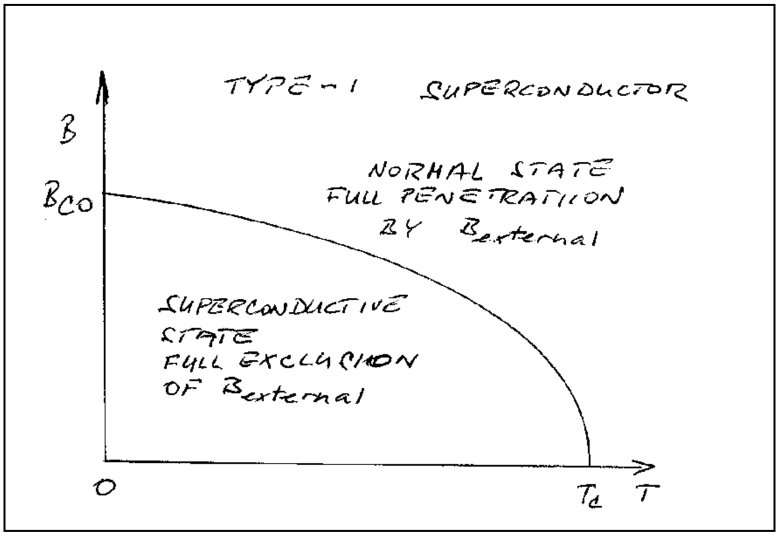
The wire can carry maximum superconductive current, I_c, corresponding to the critical magnetic field B_c at the surface of the wire, r=R,

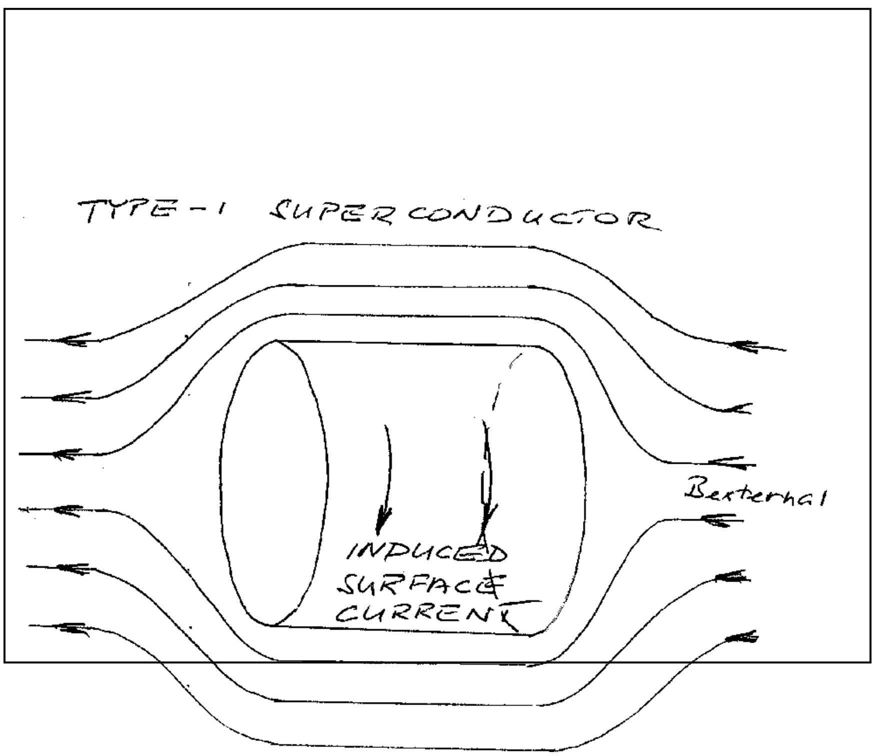
$$I_C = \frac{2\pi R B_C}{\mu_0}$$

$\mu_0 = 4\pi \times 10^{-7}$ Tm/Aisthemagneticpermeabilityoffree space.

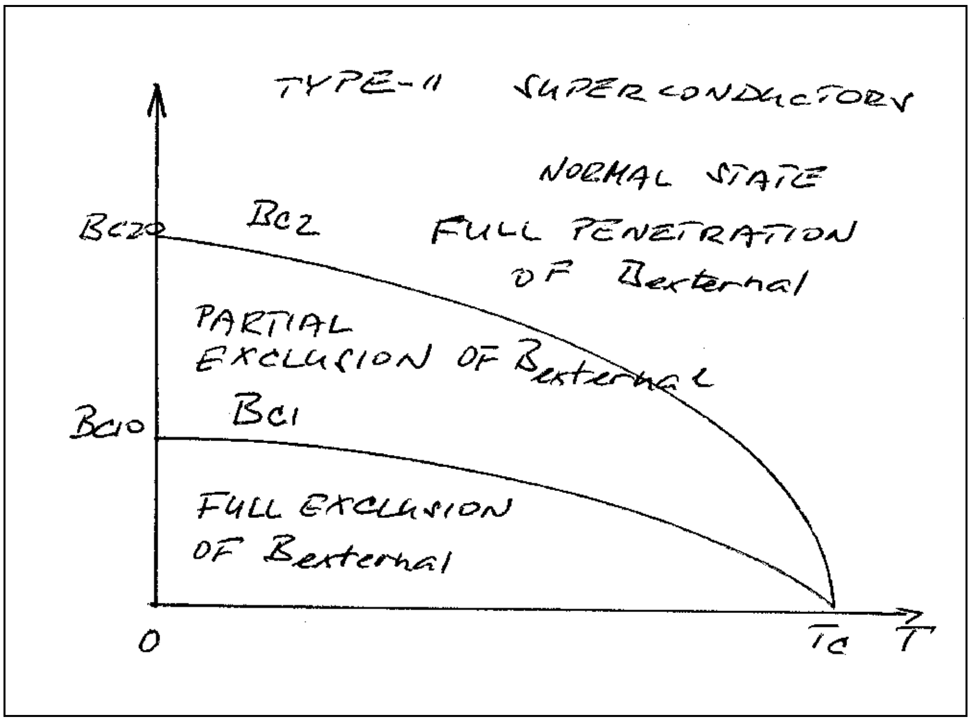
TypeIandTypeIISuperconductors exhibitdifferentmagneticresponsetoexternal magnetic field.

In **TypeIsuperconductor** the magnetic field is completely expelled from the interior for $B<B_C$.

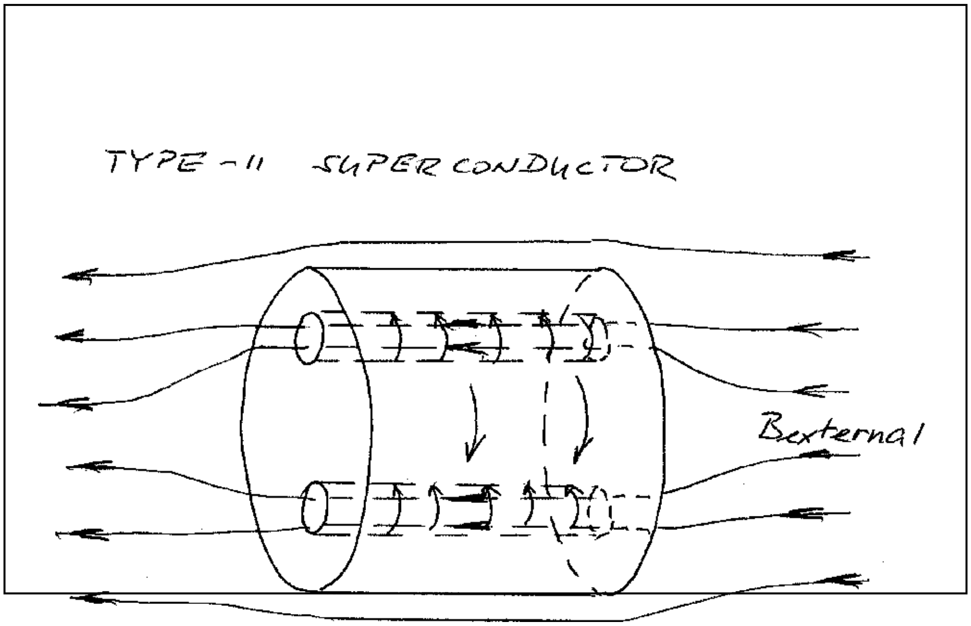




TypeIIsuperconductorshavetwovaluesofcritical magnetic field, for $B<B_{C1}$ the magnetic field is completely expelled (Type-I behavior), whereas for $B_{C1}<B<B_{C2}$ the magnetic field partially penetrates through the material.



The bulk of superconductor material breaks down into two regions: superconductive from which the external field is completely expelled, and normal through which the external field penetrates.



The normal regions are distributed as filaments filled with the external magnetic field. The flux of magnetic field through the filaments is quantized. Electric current is induced at the interface between the normal and the superconductive regions, the "surface" of filaments is "wrapped" in current which cancels the magnetic field in the superconductive regions.

The electric current is carried by the superconductive regions of Type-II material.

Superconductivemagnets

The main advantage of the superconductive magnet, in contrast to the electromagnet, is that it does not need to use (dissipate) energy to maintain the magnetic field.

However,

$$I_C = \frac{2\pi R B_C}{\mu_0}$$

In order to achieve high critical currents in superconductive magnets we need materials with high B_c. Type-I superconductors are not suitable because of low B_c. Type-II materials are used for superconductive magnets.

Superconductive magnets achieving magnetic field of about 20 Tesla use wire from niobium alloys, and operate at temperature of 4 K (cooled by liquid helium).

Quantizationofmagneticflux

Magneticfluxisquantized,thequantumoffluxis

$$\Phi = \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\,\text{weber}$$

(Wb=Tesla.m^2)

Ingeneral,themagneticfluxis

$$\Phi = n\Phi_0$$

wherenisaninteger.

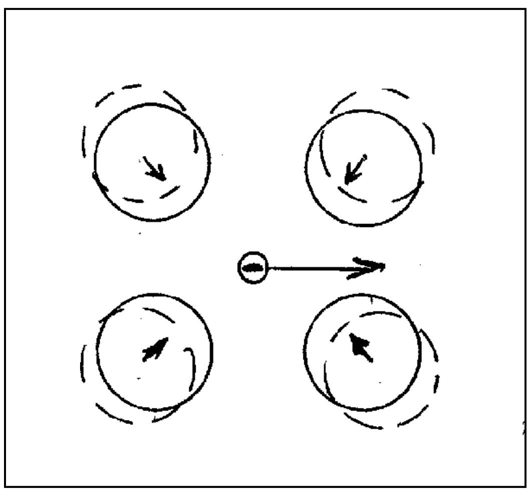
Mechanismofsuperconductivity

Isotopeeffect,$T_c$dependsonthemassofatoms

$$T_C \propto \frac{1}{\sqrt{\text{massofatomsconstitutingthecrystallattice}}}$$

Interaction between electrons and lattice atoms is critical for the existence of superconductive state. Good conductors (weak scattering from the lattice) are poor superconductors (low T_C).

Electrons on their flight through the lattice cause lattice deformation (electrons attract the positively charged lattice atoms and slightly displace them) which results in a trail of positively charged region. This positively charged region of lattice atoms attracts another electron and provides for electron-electron coupling.



Electron pairs, and not single electrons, are charge carriers in superconductors

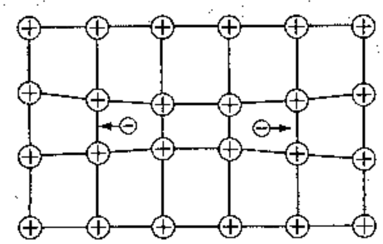


Figure 9.12 Diagram illustrating the formation of a Cooper pair. As an electron moves through the crystal it affects the positions of the ions producing a potential which is attractive to a second electron moving in the opposite direction to the first.

The electron-electron coupling is weak and can be destroyed by thermal motion of the lattice. For this reason superconductivity exists only at low temperatures.

The electron-electron coupling results in electron pairing - formationofCooperpairs.TheCooperpairsdo not have spin 1/2 and therefore do not followPauli's principle(1 electron per state). Large number of Cooper pairs can populate one collective state.
This state is stable and requires some additional energy input (thermal energy) to be destroyed. The binding energy of Cooper pairs in the collective state is several meV.

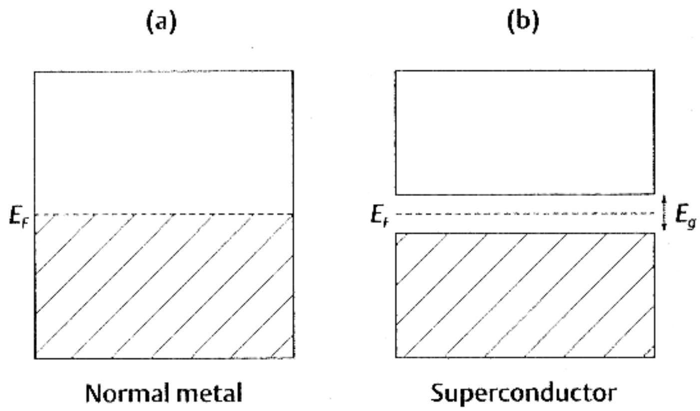


Figure 9.13 Occupation of energy levels at absolute zero in (a) a normal metal and (b) a superconductor. E_F denotes the Fermi energy. Note that in the superconductor there is a gap between the highest filled states and the lowest vacant states.

Formation of Cooper pairs is a spontaneous process resulting in lower energy state of electrons in the superconductor. In superconductors, the filled state are occupied by Coopers pairs, and the empty band, above E_g, is occupied by "broken" Cooper pairs.

The band gap E_g is a measure of binding energy of Cooper pairs, the greater binding energy, the greater T_c.

$$E_g \approx 3.53.k_B T_c$$

E_g confirmed from absorption spectra. For $hc/\lambda > E_g$ electromagnetic radiation absorbed.

“Noscattering,noresistance”

TheformationofcollectivestateofCooperpairstake place at $T<T_C$. In the collective bound state the Cooper pairs do not scatter from the lattice and the conductivity of superconductor is infinitely large.

Scattering of electrons from the lattice atoms require a change of state of electron.

In the superconductive state the current carrying species is the electron pair. For the Cooper pair to scatter it would have to change its state (like an electron in normal metal). However, the Cooper pair is coupled to a large number of other Cooper pairs and so the whole collective of Cooper pairs would have to be involved in scattering at once. This does not happen, and therefore there is no scattering of Cooper pairs and therefore the conductivity is