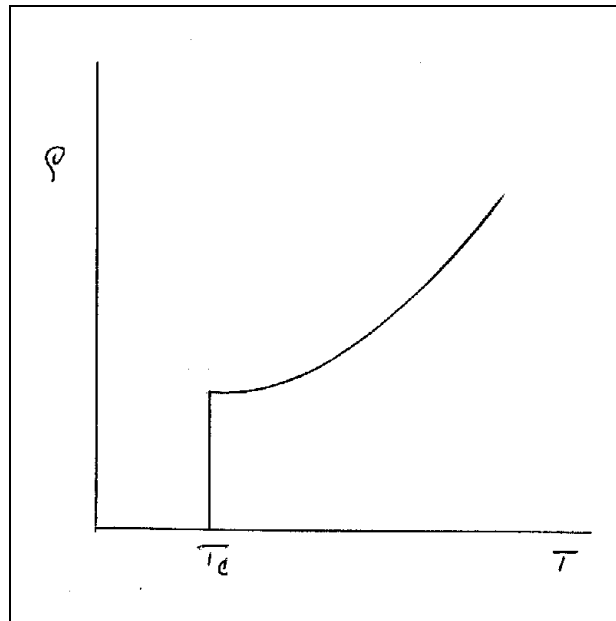


# SUPERCONDUCTIVITY

property of complete disappearance of electrical resistance in solids when they are cooled below a characteristic temperature. This temperature is called 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.

## Classical elemental superconductors

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

Until 1983 record  $T_c=23.3$  K was that of  $Nb_3Ge$  alloy.

## Progress in $T_c$ of superconductor materials with time

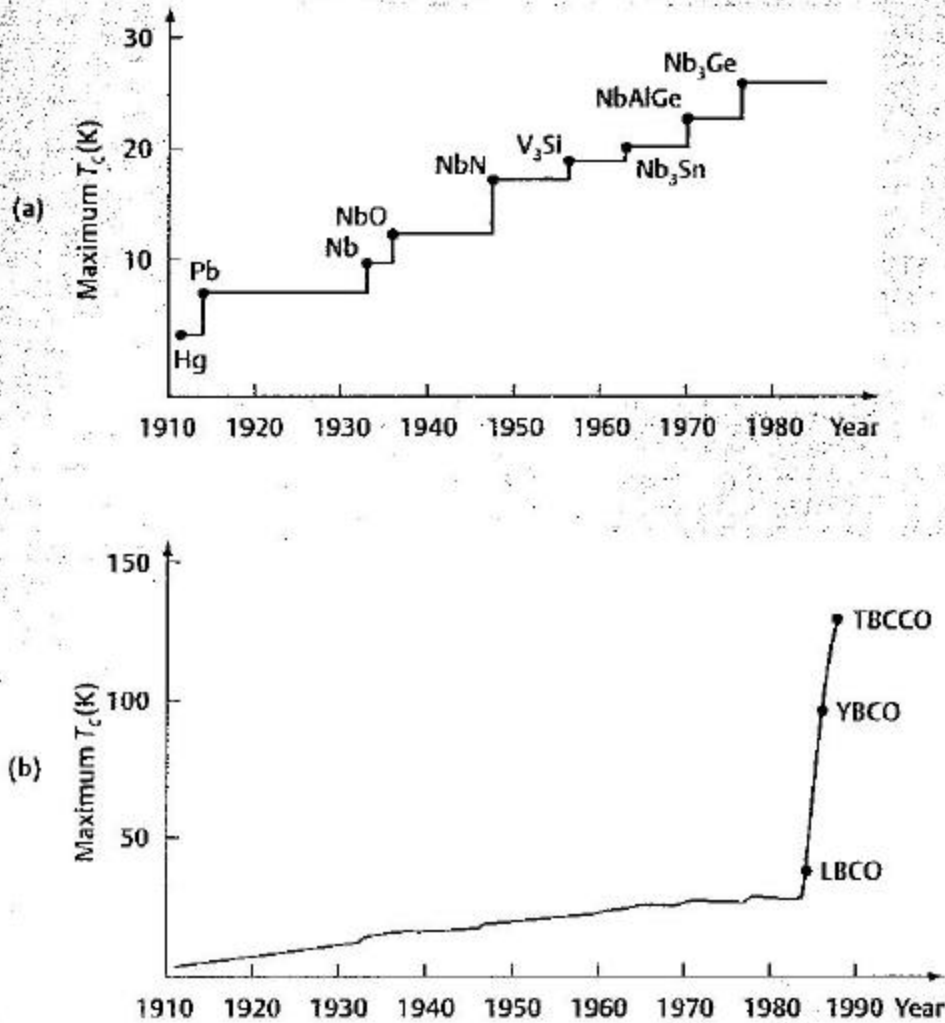


Figure 9.22 (a) Graph showing the historical rise of the maximum known critical temperature up to 1985. (b) Extended to include high-temperature superconductors.

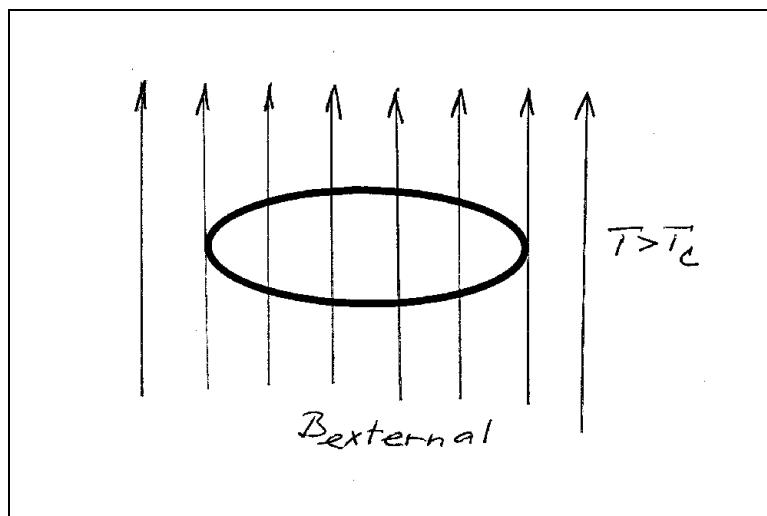
**High temperature superconductors** discovered in 1986:  $T_c=80-93$  K, parent structure  $\text{YBa}_2\text{Cu}_3\text{O}_7$ . At present the record transition temperature (TBCCO) is now at  $T_c=134$  K.

## Effect of trapped magnetic flux

Consider a ring made out of superconductive material.

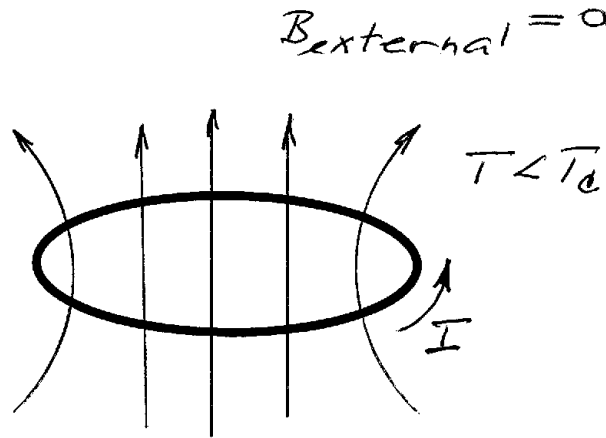
Perform the following thought experiment:

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



2. Reduce the temperature so that  $T < T_c$ .
3. Remove the external magnetic field.

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

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

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

where  $E$  is the electric field along the closed loop,  $\Phi$  is the magnetic flux through the opening of the ring.

Before the external magnetic field was turned off there was a magnetic flux  $\Phi = B \cdot (\text{area})$  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

$$\oint \vec{E} \cdot d\vec{l} = 0$$

and therefore,  
the right side of Faraday's equation

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

which means that

$$\Phi = B(\text{area}) = \text{const}$$

The magnetic flux  $\Phi$  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.

The induced current is called the persistent current.

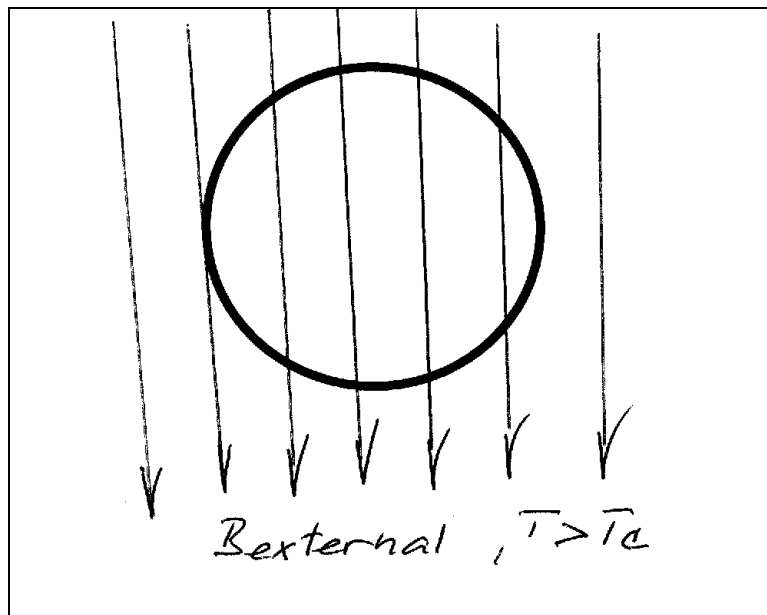
The current persists, it does not decay because the resistance of the ring is zero. Actually no decrease of current was observed over the period of three years! Theoretically, the relaxation time of current carriers in the superconductor is greater than the age of universe.

## Meissner effect

*expulsion of magnetic field from the interior of the superconductor*

Thought experiment

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.



On the basis of Faraday's law,

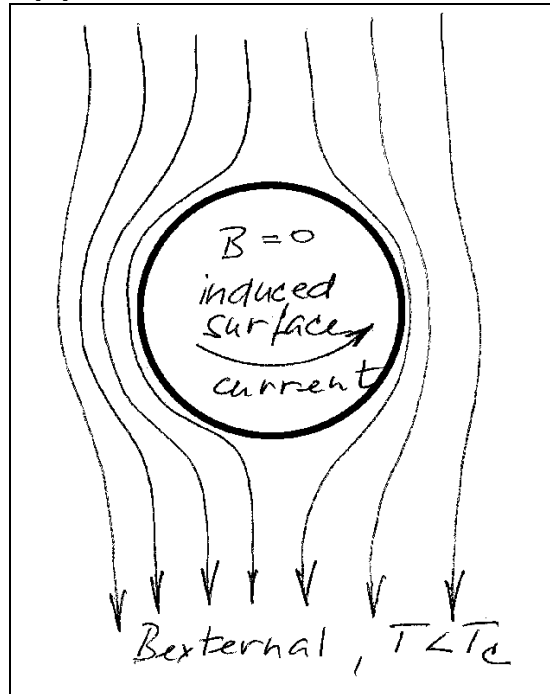
$$\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi}{dt}$$

one would expect that at  $T < T_c$  the magnetic field 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).

This is what happens:



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!

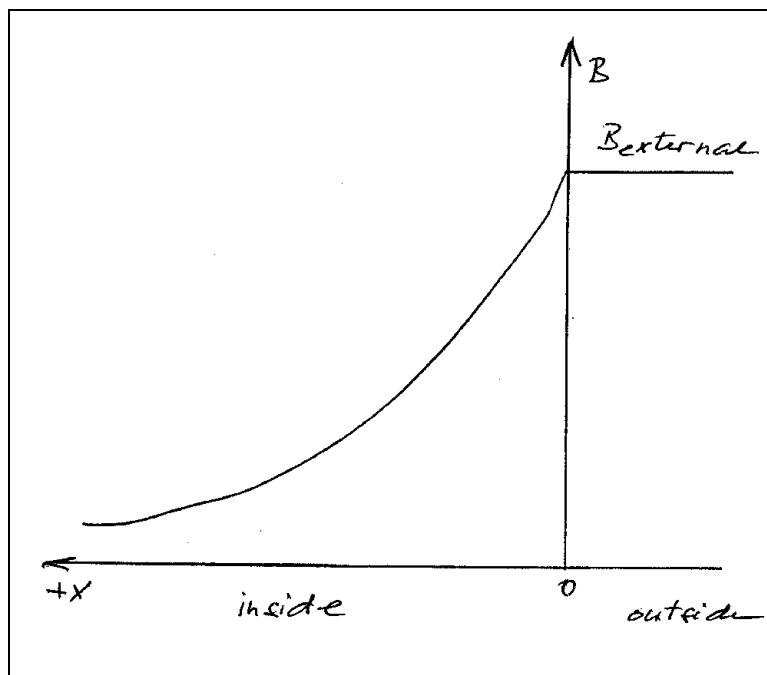
This electric current at the surface of the superconductor appears at  $T < T_c$  in order that  $B=0$  inside the superconductor.

## Penetration of magnetic field below the surface of superconductors

The surface current is distributed in the surface layer, 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,

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

$\lambda$  = penetration distance at temperature T;



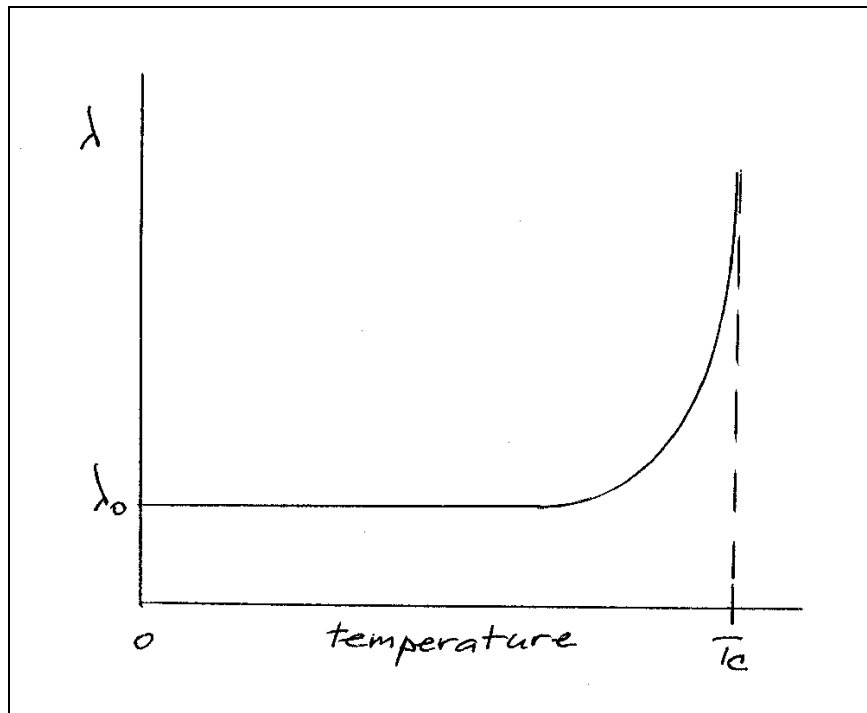
## Temperature dependence of penetration distance

$\lambda$  = penetration distance at temperature  $T$ ;

$\lambda_0$  = penetration distance at temperature  $T=0$ .

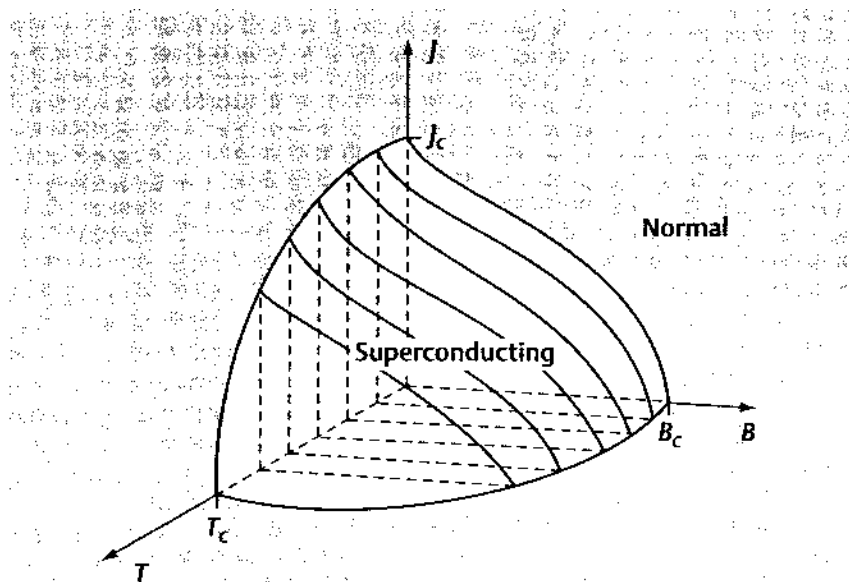
$$\lambda = \frac{\lambda_0}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}$$

$\lambda_0 = 30 - 130$  nm, depending on the superconductor material



## The magnetic properties of 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.



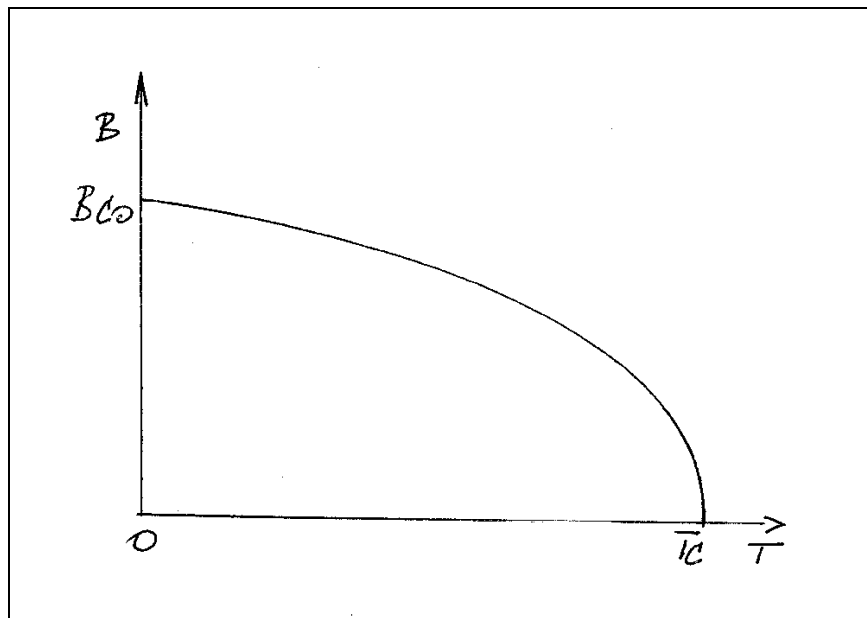
**Figure 9.4** The ability of a material to superconduct depends on three factors: the temperature,  $T$ , the magnetic field strength,  $B$ , and the current density  $J$ .  $T_c$  is the critical temperature in the absence of an external magnetic field and with no current flowing in the sample,  $B_c$  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.

## Critical magnetic field

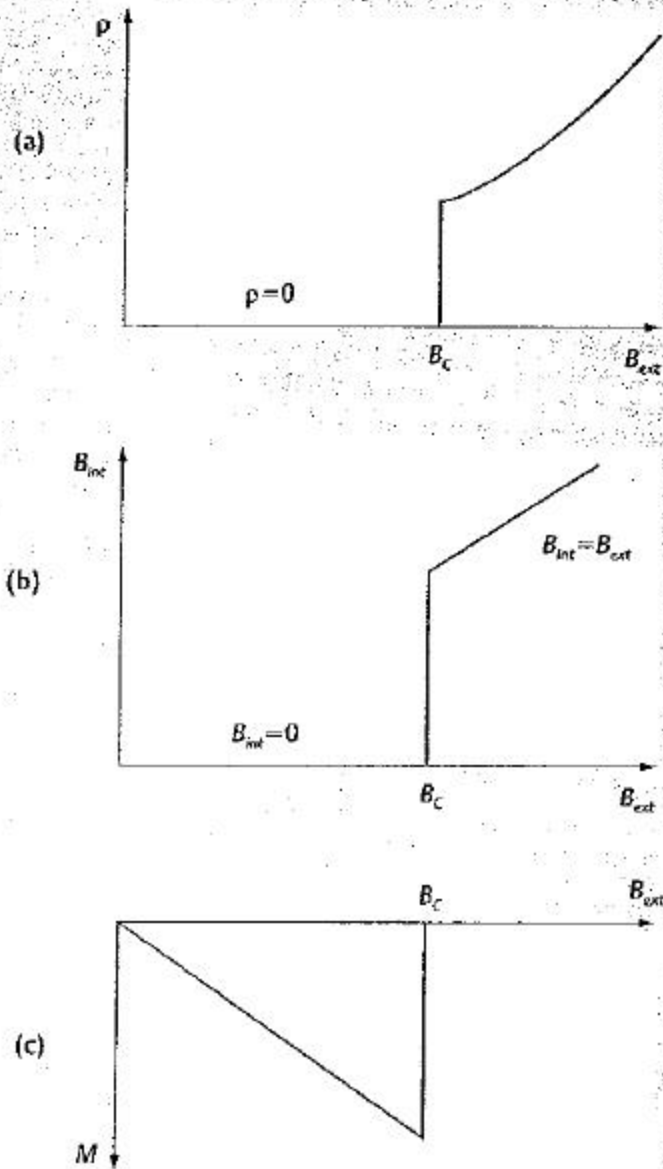
The critical magnetic field depends upon the temperature,

$$B_c(T) = B_{c0} \left( 1 - \left( \frac{T}{T_c} \right)^2 \right)$$

$B_{c0}$  = critical magnetic field at  $T=0$ .



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  $\rho$ , (b) the internal magnetic field strength  $B_{int}$  and (c) the magnetization  $M$  as a function of the external magnetic field strength  $B_{ext}$ .

### ***Critical current***

Superconductive state is destroyed by magnetic field.

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,  $r=R$ ,

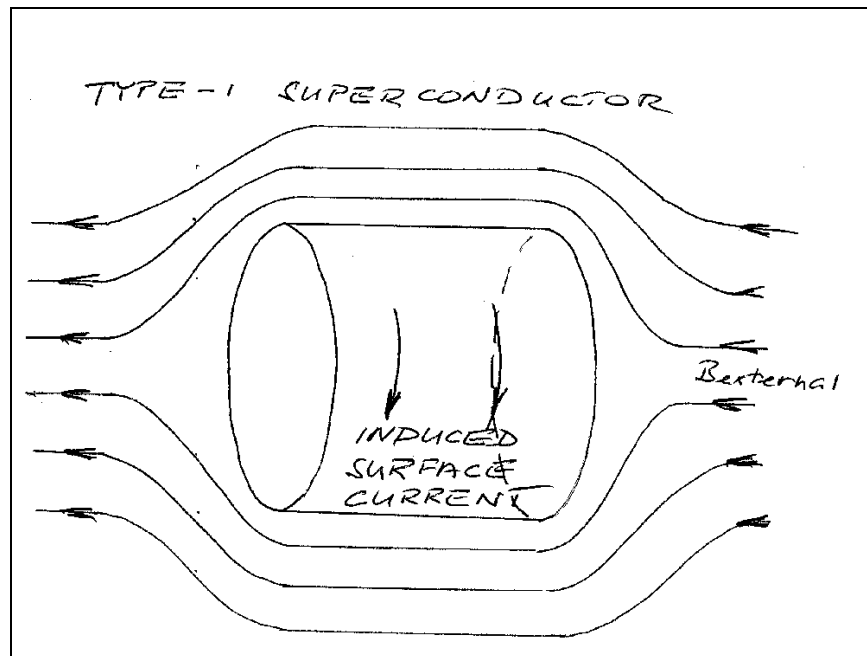
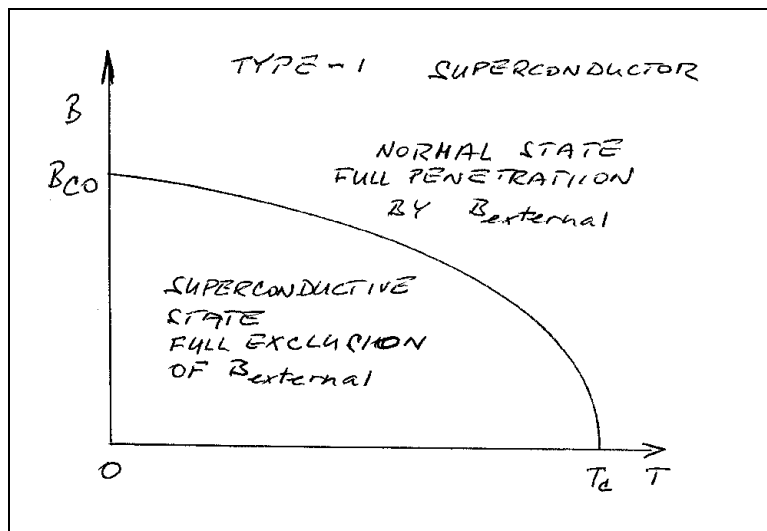
$$I_c = \frac{2\pi R B_c}{\mu_0}$$

$\mu_0 = 4\pi \cdot 10^{-7}$  Tm/A is the magnetic permeability of free space.

## Type I and Type II Superconductors

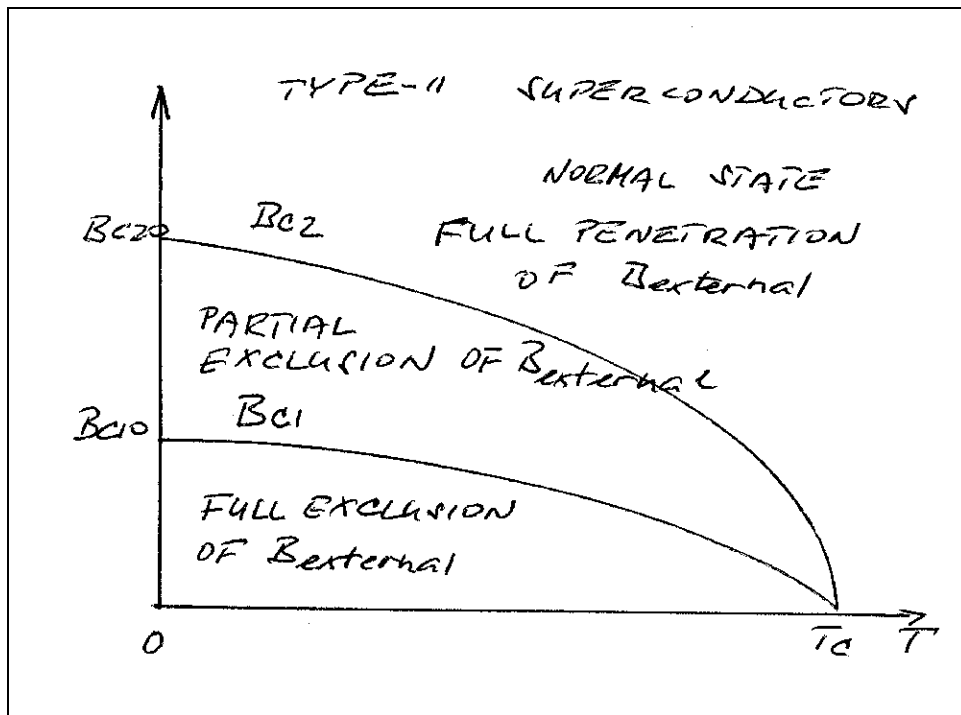
exhibit different magnetic response to external magnetic field.

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

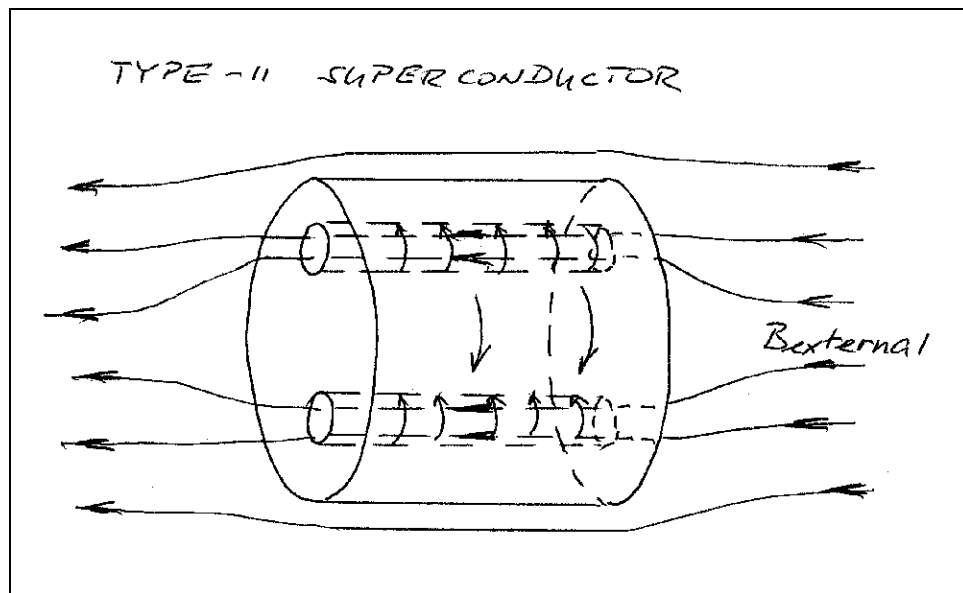




**Type II superconductors** have two values of critical magnetic field, for  $B < B_{C1}$  the magnetic field is completely expelled (Type-I behavior), whereas for  $B_{C1} < B < B_{C2}$  the magnetic field partially penetrates through the material.



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.

## Superconductive magnets

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).

## Quantization of magnetic flux

Magnetic flux is quantized, the quantum of flux is

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

(Wb=Tesla.m<sup>2</sup>)

In general, the magnetic flux is

$$\Phi = n\Phi_0$$

where n is an integer.

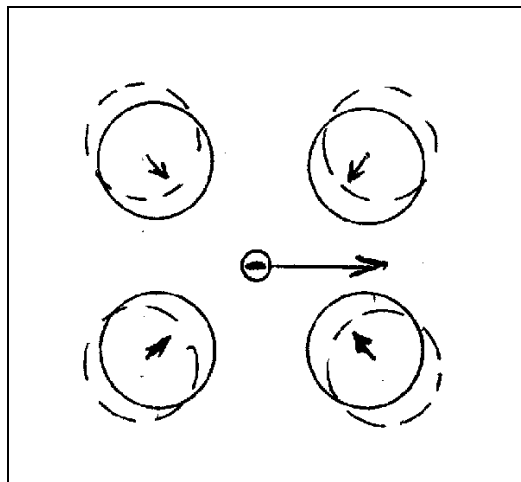
## Mechanism of superconductivity

Isotope effect,  $T_c$  depends on the mass of atoms

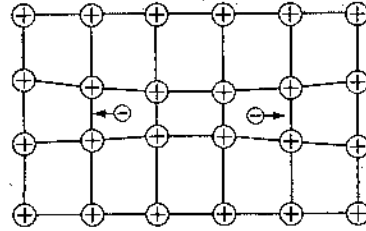
$$T_c \propto \frac{1}{\sqrt{\text{mass of atoms constituting the crystal lattice}}}$$

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.



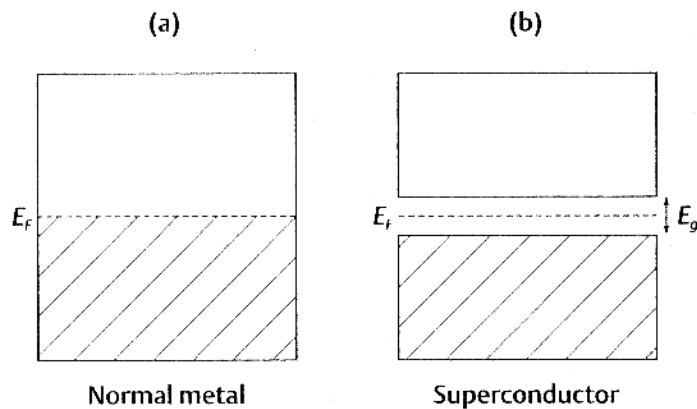
Electron pairs, and not single electrons, are charge carriers in superconductors



**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 - formation of Cooper pairs. The Cooper pairs do not have spin 1/2 and therefore do not follow Pauli'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 Cooper 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  $T_c$ .

$$E_g = 3.53 \cdot k_B T_c$$

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

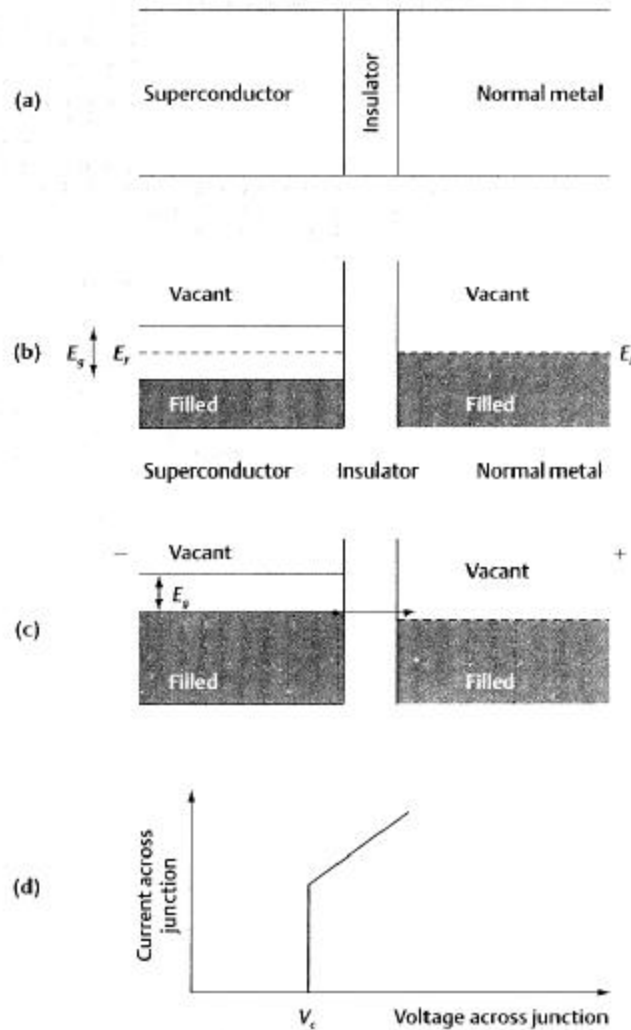
## ***“No scattering, no resistance”***

The formation of collective state of Cooper pairs take 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 infinite.

## Current-voltage characteristics of metal-insulator-superconductor junction

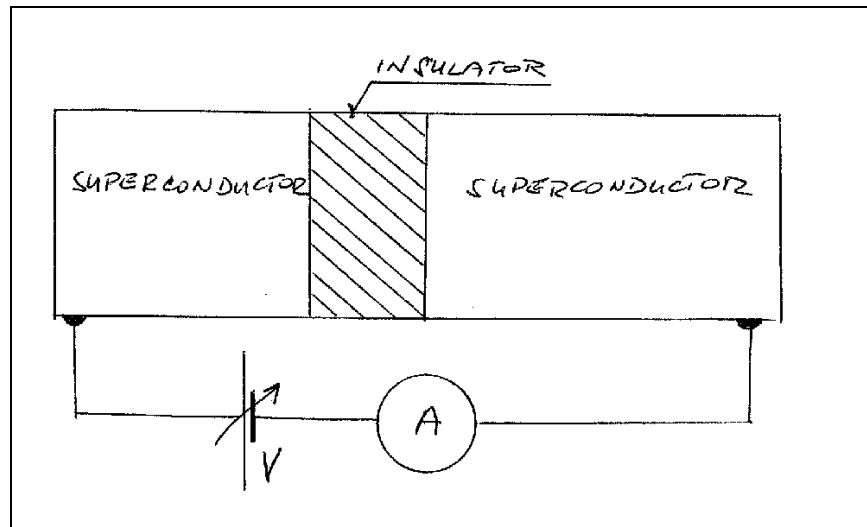


**Figure 9.14** (a) A schematic diagram of a tunnel junction between a superconductor and a normal metal. Tunnelling can occur if there are vacant states on one side of the junction at the same (or lower) energy as occupied states on the other side. (b) The electron energy bands at zero bias and at a temperature of 0 K. Note that there are no allowed energy levels in the insulator for the energy range shown. This means that electrons can only pass from one side to the other by tunnelling through the insulator layer. Tunnelling is prohibited in this instance because there are no suitable vacant states on either side of the insulator. (c) When the junction is subject to a bias  $V \geq E_g/2e$ , electrons from the superconductor can tunnel into vacant states in the normal metal and a current flows across the junction. (d) A plot of current against voltage shows that for a voltage less than the critical value  $V_c$  there is no current across the junction, but at the voltage  $V_c$  there is a sharp increase in current.



## Josephson effect

Consider two superconductors separated by a thin insulating layer, few nm thick.



Brian Josephson noted (1962) that

1. Electron pairs in the two superconductors can form a single collective state and the electron pairs can tunnel through the insulating layer.

DC Josephson effect = electron tunneling current across the junction in the absence of applied voltage.

2. If a DC voltage bias is applied across the junction, there is an AC current through the junction that oscillates with frequency

$$f = \frac{2e}{h} V$$

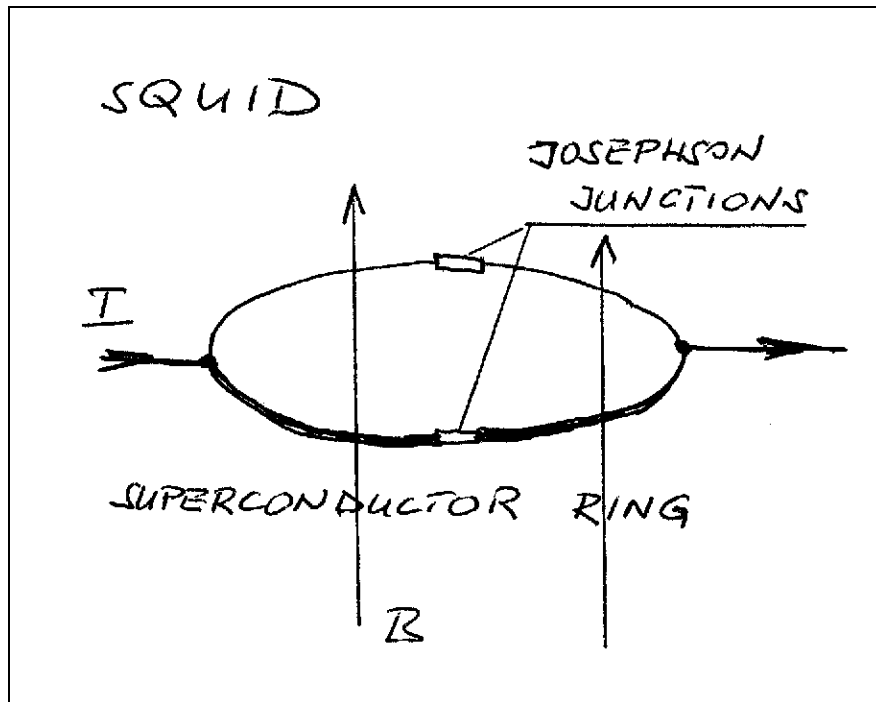
The existence of ac current through the biased junction = AC Josephson effect.

The AC Josephson effect provides a method for the most accurate measurement of the electric potential difference because  $f$  can be determined accurately by “frequency counters”.

The value of  $2e/h=483.6 \text{ MHz}/\mu\text{V}$ .

## SQUID

=Superconductive QUantum Interference Device  
consist of two Josephson junctions forming a ring.



SQUIDS are used to measure extremely weak magnetic fields (for example, magnetic fields created by currents in the brain in response to various stimuli or thinking).