Εισαγωγή στην Υπεραγωγιμότητα

P. Poulopoulos, 26 Ιουνίου 2020, Πάτρα

- Πείραμα καθ. Κ. Πολίτης

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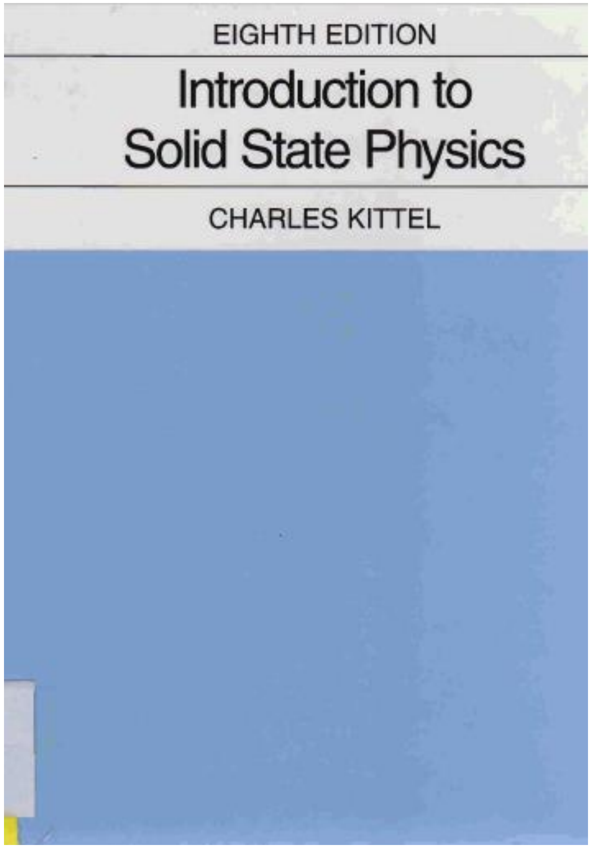
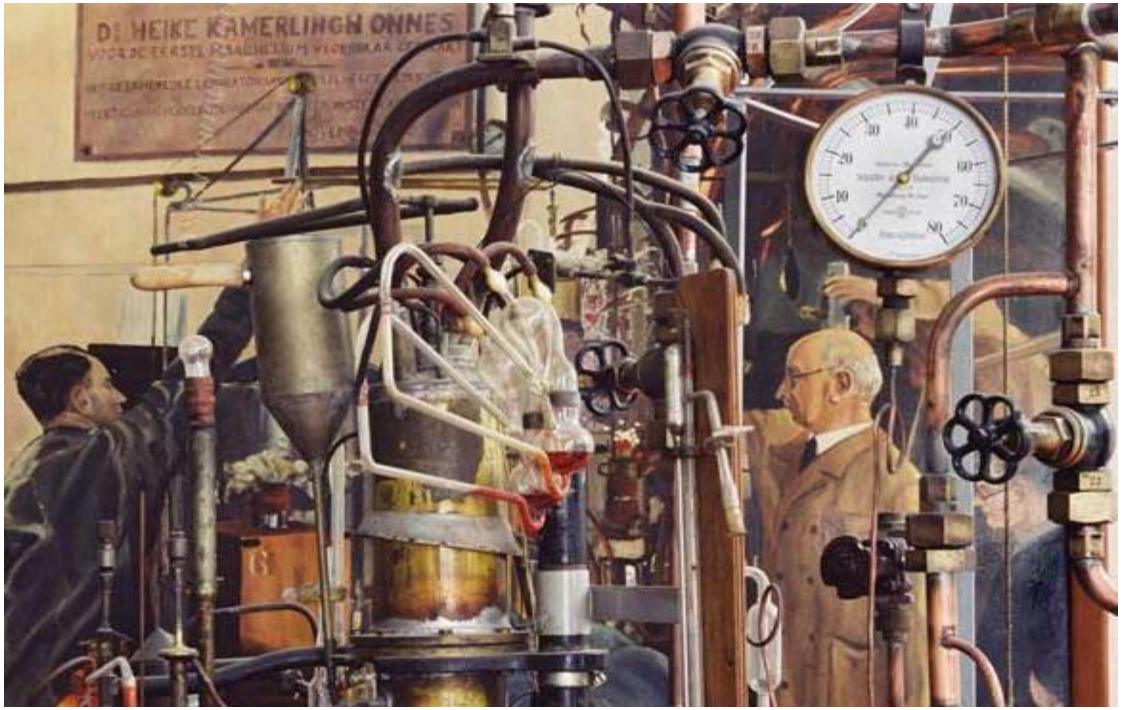
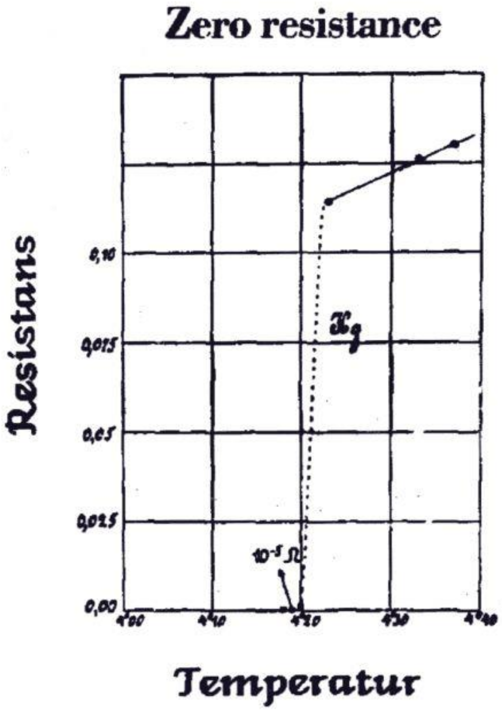


Η διάλεξη αυτή γίνεται διαδικτυακά στα πλαίσια των προβλημάτων του Covid-19. Οι διαφάνειες είναι μόνο για διευκόλυνση των φοιτητών για το εξ αποστάσεως μάθημα και δεν έχουν κανένα στόχο εμπορικής εκμετάλλευσης. Επίσης παρακαλώ τους φοιτητές να τις κρατήσουν μόνο για τους εαυτούς τους και τις εξετάσεις τους.

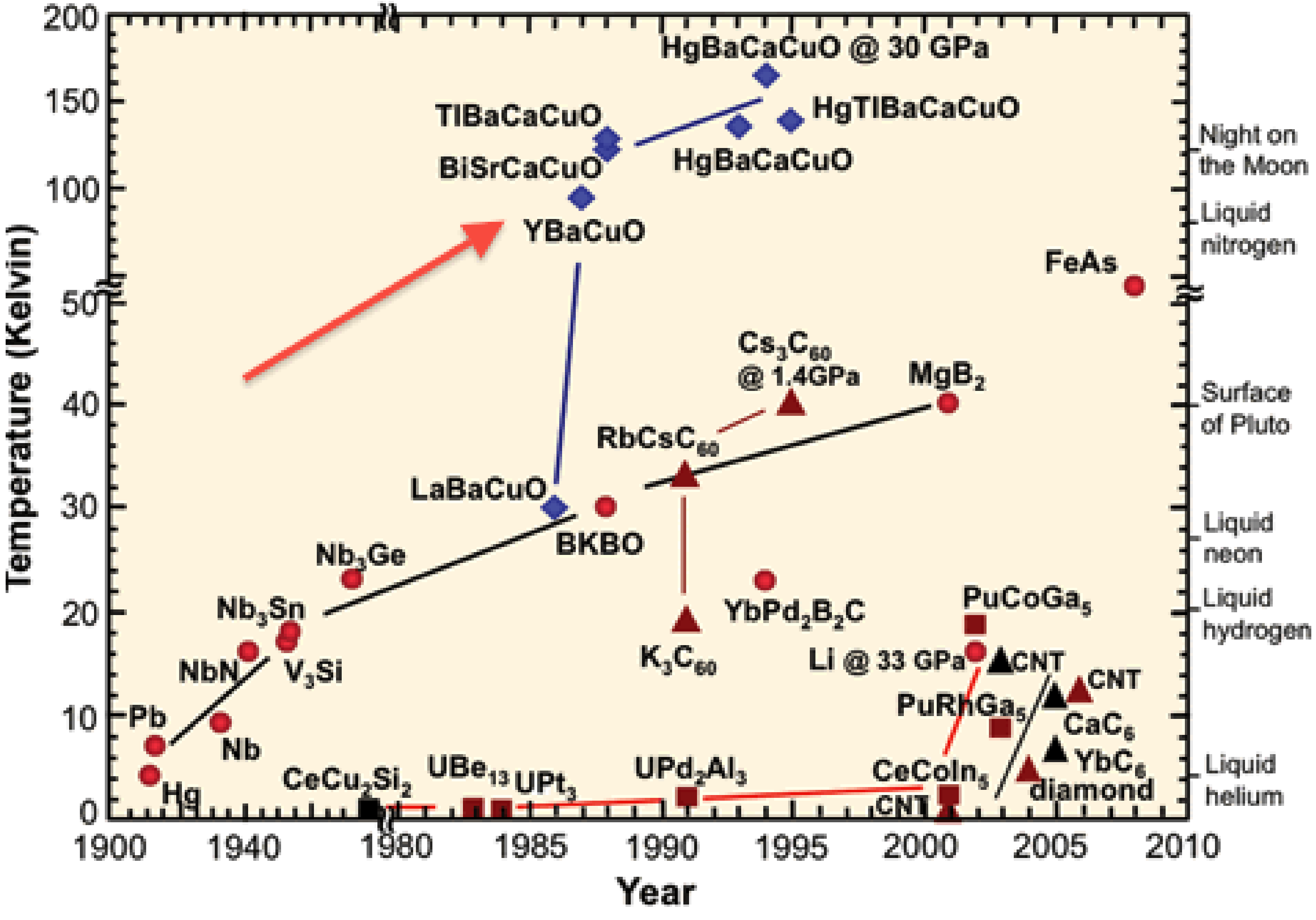
Some Introduction

Basically, the resistivity of some metals, alloys and ceramics drops suddenly to 0 at sufficient low temperatures. This phenomenon called **superconductivity** was found in 1911 by Kamerlingh Onnes in Leiden 1911. Three years earlier the liquidification of He was achieved.



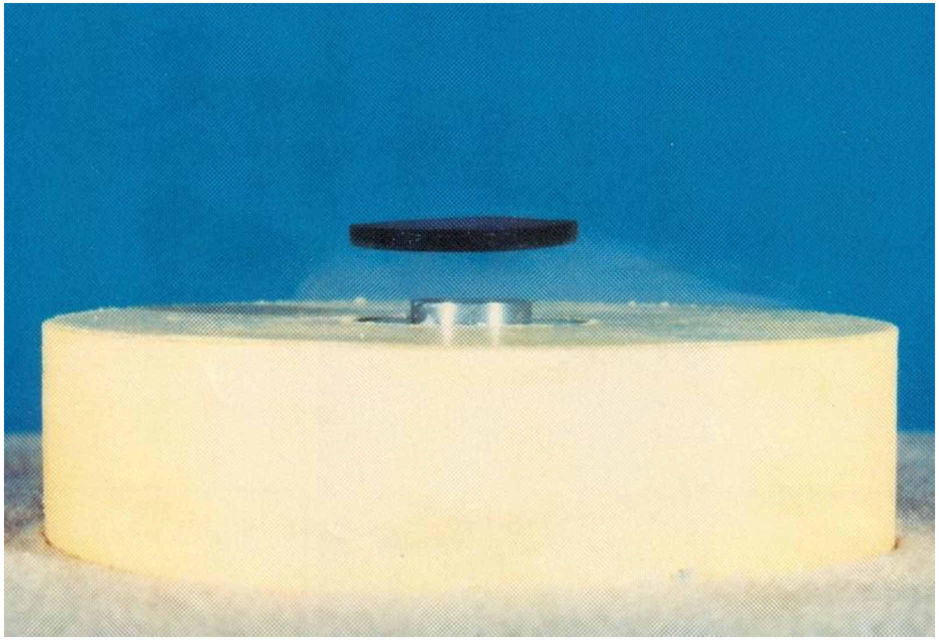


Superconductivity Calendar



Meissner Effect

A superconductor in a weak magnetic field acts as a perfect diamagnet, $\chi = -1$. When a sample is placed in a field and cools down through Tc the mugnetic flux is ejected out of the specimen. This **Meissner effect** can be used for magnetic levitation (photo from March 1987).



The superconducting state is an ordered state of the conduction electrons of the metal. The order is in the formation of loosely associated pairs of electrons. The electrons are ordered at temperatures below the transition temperature, and they are disordered above the transition temperature.

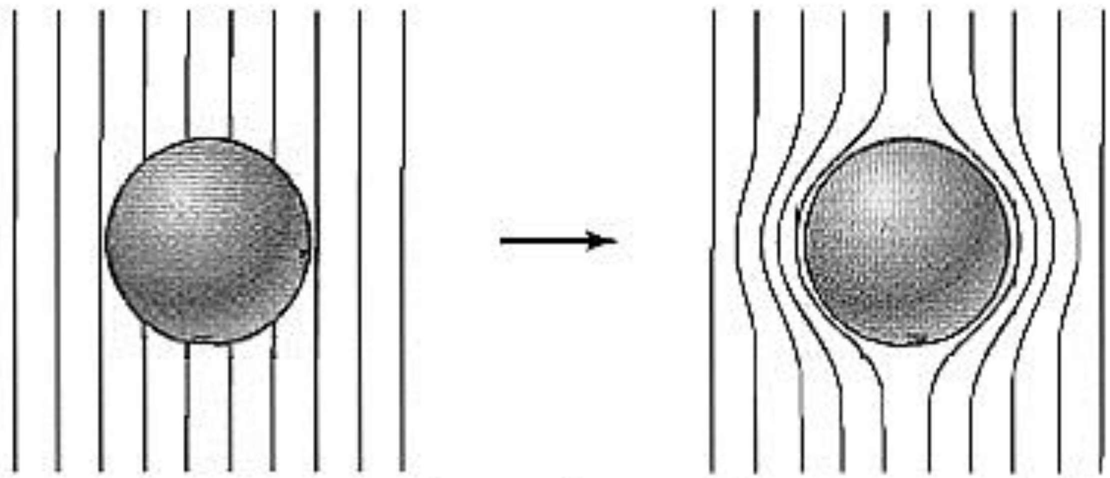


Figure 2 Meissner effect in a superconducting sphere cooled in a constant applied magnetic field; on passing below the transition temperature the lines of induction **B** are ejected from the sphere.

Type I and type II Superconductors

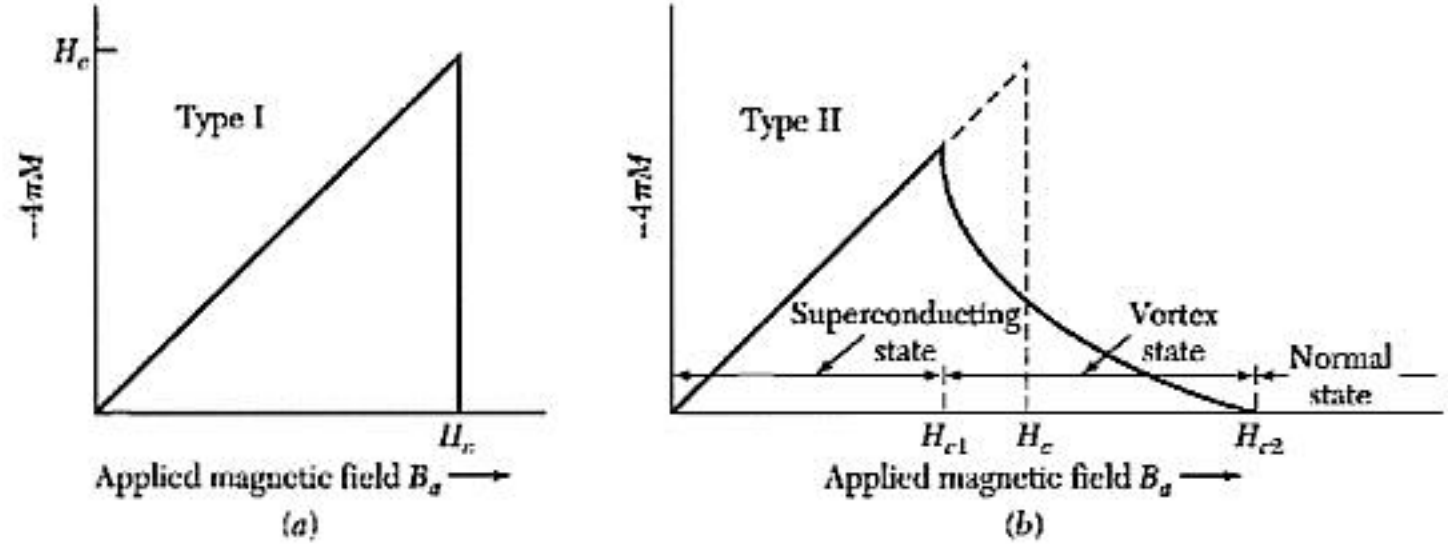


Figure 4 (a) Magnetization versus applied magnetic field for a bulk superconductor exhibiting a complete Meissner effect (perfect diamagnetism). A superconductor with this behavior is called a type I superconductor. Above the critical field H_c the specimen is a normal conductor and the magnetization is too small to be seen on this scale. Note that minus $4\pi M$ is plotted on the vertical scale: the negative value of M corresponds to diamagnetism. (b) Superconducting magnetization curve of a type II superconductor. The flux starts to penetrate the specimen at a field H_{c1} lower than the thermodynamic critical field H_c. The specimen is in a vortex state between H_{c1} and H_{c2}, and it has superconducting electrical properties up to H_{c2}. Above H_{c2} the specimen is a normal conductor in every respect, except for possible surface effects. For given H_c the area under the magnetization curve is the same for a type II superconductor as for a type I. (CGS units in all parts of this figure.)

1950: The isotopic effect

Isotope Effect

It has been observed that the critical temperature of superconductors varies with isotopic mass. In mercury T_c varies from 4.185 K to 4.146 K as the average atomic mass M varies from 199.5 to 203.4 atomic mass units. The transition temperature changes smoothly when we mix different isotopes of the same element. The experimental results within each series of isotopes may be fitted by a relation of the form

$$M^{\alpha} T_c = \text{constant} \quad . \tag{2}$$

Observed values of α are given in Table 4.

Table 4 Isotope effect in superconductors

Experimental values of α in $M^{\alpha} T_c$ = constant, where M is the isotopic mass.

Substance	α	Substance	α
Zn	0.45 ± 0.05	Ru	0.00 ± 0.05
Cd	0.32 ± 0.07	Os	0.15 ± 0.05
Sn	0.47 ± 0.02	Mo	0.33
Hg	0.50 ± 0.03	Nb_3Sn	0.08 ± 0.02
Pb	0.49 ± 0.02	Zr	0.00 ± 0.05

London Theory

Could we find a simple equation such as Ohm's law **j** = σ**E** for the Meissner effect?

This is the London equation: $j = (-1/\mu_0 \lambda_L{}^2)A$

Lamda is the **penetration depth** of a magnetic field in the superconductor

$$B(x) = B(0)e^{-x/\lambda_L}$$

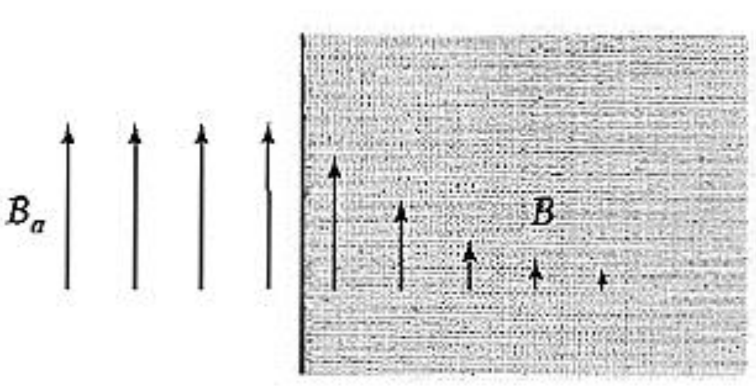


Figure 13 Penetration of an applied magnetic field into a semi-infinite superconductor. The penetration depth λ is defined as the distance in which the field decreases by the factor e^{-1}. Typically, λ ≈ 500 Å in a pure superconductor.

Coherence Length ξ

The London penetration depth λ_L is a fundamental length that characterizes a superconductor. An independent length is the **coherence length** ξ. The coherence length is a measure of the distance within which the superconducting electron concentration cannot change drastically in a spatially-varying magnetic field.

We define an **intrinsic coherence length** ξ_0 related to the critical modulation by $\xi_0 = 1/q_0$. We have

$$\xi_0 = \hbar^2 k_F / 2mE_g = \hbar v_F / 2E_g \ , \qquad (16b)$$

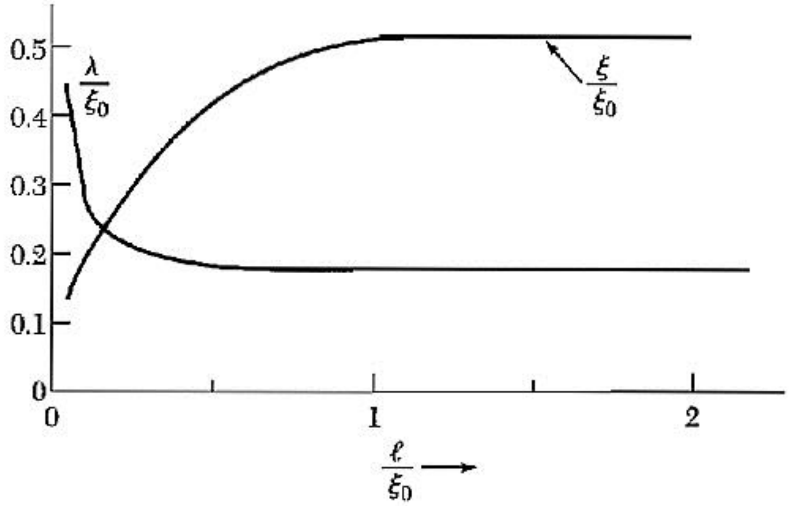
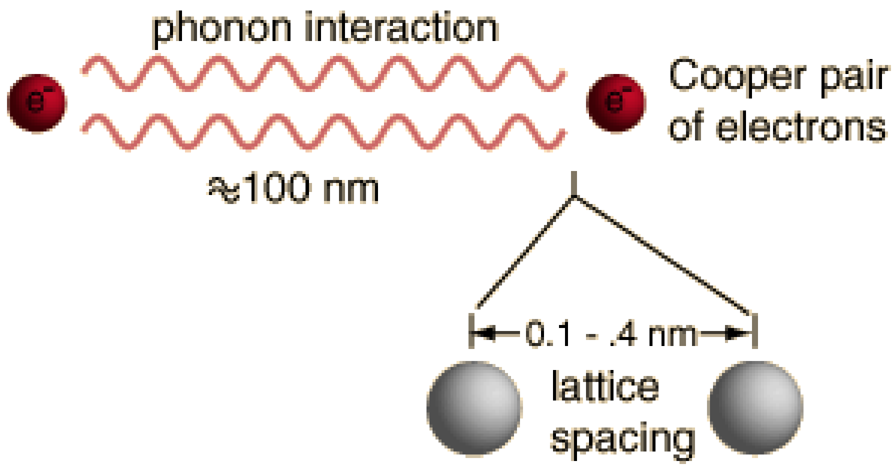


Figure 14 Penetration depth λ and the coherence length ξ as functions of the mean free path ℓ of the conduction electrons in the normal state. All lengths are in units of ξ_0, the intrinsic coherence length. The curves are sketched for $\xi_0 = 10\lambda_L$. For short mean free paths the coherence length becomes shorter and the penetration depth becomes longer. The increase in the ratio $\kappa\lambda/\xi$ favors type II superconductivity.

The BCS Theory of Superconductivity

The microscopic theory put forward by Bardeen, Cooper and Schruffier (BCS) is the basis of quantum theory of Superconductivity. The fundamental postulate of BCS theory is that when an attractive interaction between two electrons by means of phonon exchange dominates the repulsive coulomb interaction then the superconducting state is formed.

Electron-phonon-electron interaction : During an interaction of an electron with a positive ion of the lattice through electrostatic coulomb force, some electron momentum get transferred. As a result, these ions set up elastic wave in the lattice due to distortion. If another electron happens to pass through this region then the interaction between two occurs which in its effect lowers the energy of the second electron. The two electrons interact via the lattice distortion or the phonon field resulting in the lowering of energy of the electron which implies the force between two electrons is attractive. This interaction is strongest when two electrons have equal and opposite moments and spin and this pair is known as **cooper pair**.



Cooper pairs

When the temperature of the specimen is lowered, if the attractive force between two electrons via a phonon exceeds coulomb repulsion between them, then a weakly bound cooper pair is formed having the binding energy of the order of 10^{-3} eV. The energy of Cooper pair is less than the energy of the pair in free state. The binding energy of cooper pair is called energy bang gap, E_g. When $h\nu \geq E_g$ strong absorption occurs as the cooper pairs break apart.

The electrons in cooper pair have opposite spins so the total spin of the pair is zero. As a result cooper pairs are bosons whereas electrons are fermions.

The BCS Theory of Superconductivity

1. An attractive interaction between electrons can lead to a ground state separated from excited states by an energy gap. The critical field, the thermal properties, and most of the electromagnetic properties are consequences of the energy gap.

2. The electron-lattice-electron interaction leads to an energy gap of the observed magnitude. The indirect interaction proceeds when one electron interacts with the lattice and deforms it; a second electron sees the deformed lattice and adjusts itself to take advantage of the deformation to lower its energy. Thus the second electron interacts with the first electron via the lattice deformation.

3. The penetration depth and the coherence length emerge as natural consequences of the BCS theory. The London equation is obtained for magnetic fields that vary slowly in space. Thus the central phenomenon in superconductivity, the Meissner effect, is obtained in a natural way.

4. The criterion for the transition temperature of an element or alloy involves the electron density of orbitals $D(\epsilon_F)$ of one spin at the Fermi level and the electron-lattice interaction U, which can be estimated from the electrical resistivity because the resistivity at room temperature is a measure of the electron-phonon interaction. For $UD(\epsilon_F) \ll 1$ the BCS theory predicts

$$T_c = 1.14\theta \exp[-1/UD(\epsilon_F)] \ , \qquad (18)$$

where θ is the Debye temperature and U is an attractive interaction. The result for T_c is satisfied at least qualitatively by the experimental data. There is an interesting apparent paradox: the higher the resistivity at room temperature the higher is U, and thus the more likely it is that the metal will be a superconductor when cooled.

5. Magnetic flux through a superconducting ring is quantized and the effective unit of charge is $2e$ rather than e. The BCS ground state involves pairs of electrons; thus flux quantization in terms of the pair charge $2e$ is a consequence of the theory.

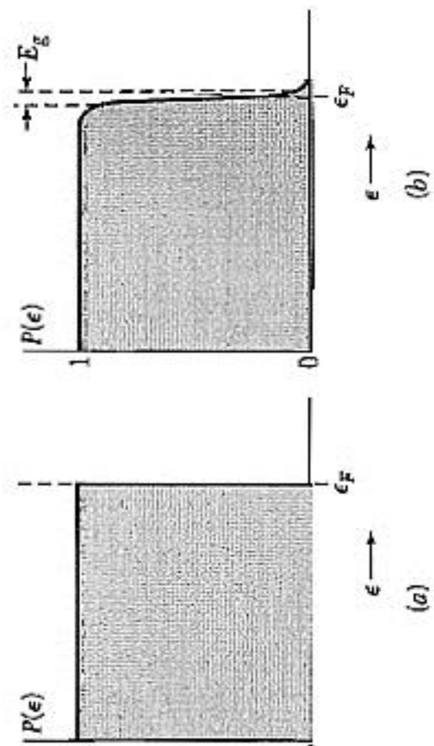


Figure 15 (a) Probability P that an orbital of kinetic energy ϵ is occupied in the ground state of the noninteracting Fermi gas; (b) the BCS ground state differs from the Fermi state in a region of width of the order of the energy gap E_g. Both curves are for absolute zero.

Flux Quantization in a sc ring

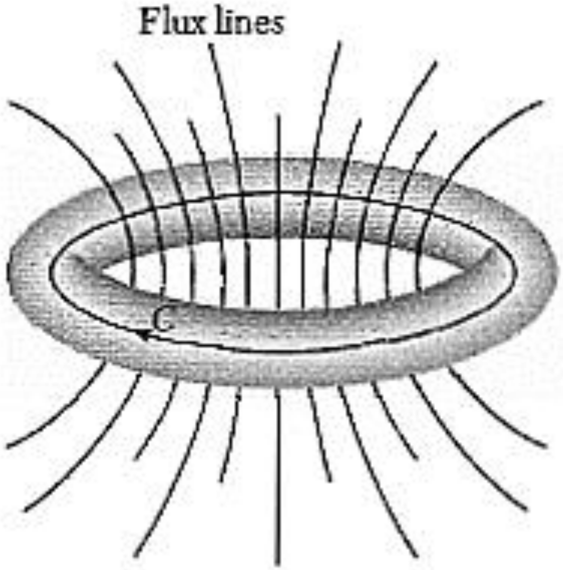


Figure 16 Path of integration C through the interior of a superconducting ring. The flux through the ring is the sum of the flux Φ_{ext} from external sources and the flux Φ_{sc} from the superconducting currents which flow in the surface of the ring; $\Phi = \Phi_{ext} + \Phi_{sc}$. The flux Φ is quantized. There is normally no quantization condition on the flux from external sources, so that Φ_{sc} must adjust itself appropriately in order that Φ assume a quantized value.

(SI) $$\Phi_0 = 2\pi\hbar/2e \cong 2.0678 \times 10^{-15} \text{ tesla m}^2 \ .$$

This flux quantum is called a **fluxoid** or **fluxon**.

Josephson Effect

Josephson Superconductor Tunneling

Under suitable conditions we observe remarkable effects associated with the tunneling of superconducting electron pairs from a superconductor through a layer of an insulator into another superconductor. Such a junction is called a weak link. The effects of pair tunneling include:

Dc Josephson effect. A dc current flows across the junction in the absence of any electric or magnetic field.

Ac Josephson effect. A dc voltage applied across the junction causes rf current oscillations across the junction. This effect has been utilized in a precision determination of the value of $\hbar/e$. Further, an rf voltage applied with the dc voltage can then cause a dc current across the junction.

Macroscopic long-range quantum interference. A dc magnetic field applied through a superconducting circuit containing two junctions causes the maximum supercurrent to show interference effects as a function of magnetic field intensity. This effect can be utilized in sensitive magnetometers.

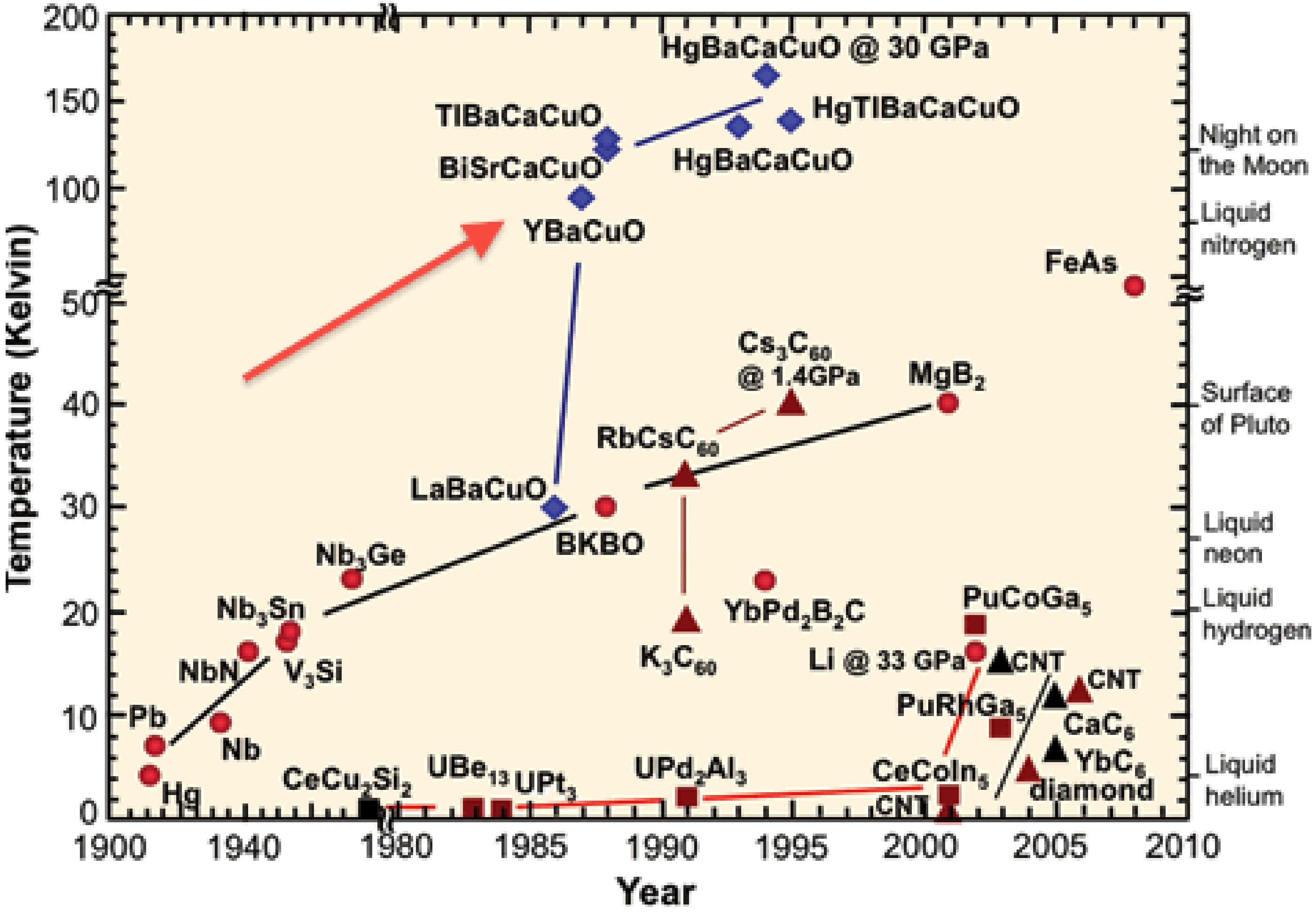
High Tc Superconductors

HIGH-TEMPERATURE SUPERCONDUCTORS

High T_c or HTS denotes superconductivity in materials, chiefly copper oxides, with high transition temperatures, accompanied by high critical currents and magnetic fields. By 1988 the long-standing 23 K ceiling of T_c in intermetallic compounds had been elevated to 125 K in bulk superconducting oxides; these passed the standard tests for superconductivity—the Meissner effect, ac Josephson effect, persistent currents of long duration, and substantially zero dc resistivity. Memorable steps in the advance include:

$BaPb_{0.75}Bi_{0.25}O_3$	$T_c = 12$ K	[BPBO]
$La_{1.85}Ba_{0.15}CuO_4$	$T_c = 36$ K	[LBCO]
$YBa_2Cu_3O_7$	$T_c = 90$ K	[YBCO]
$Tl_2Ba_2Ca_2Cu_3O_{10}$	$T_c = 120$ K	[TBCO]
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$	$T_c = 138$ K	

Superconductivity Calendar



Superconductivity Applications