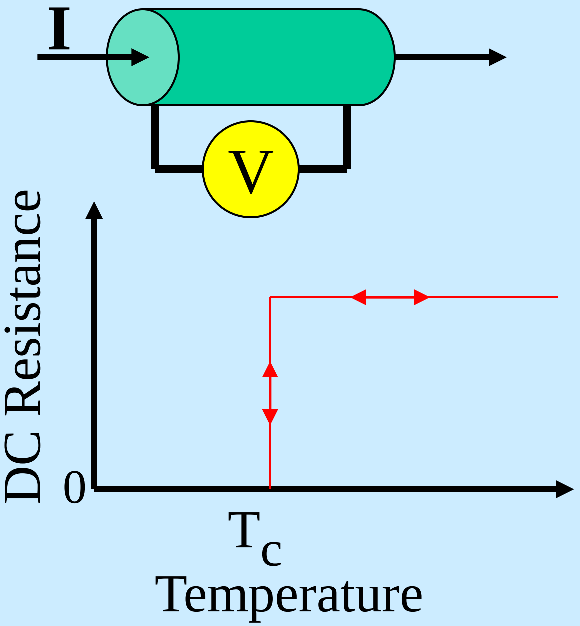
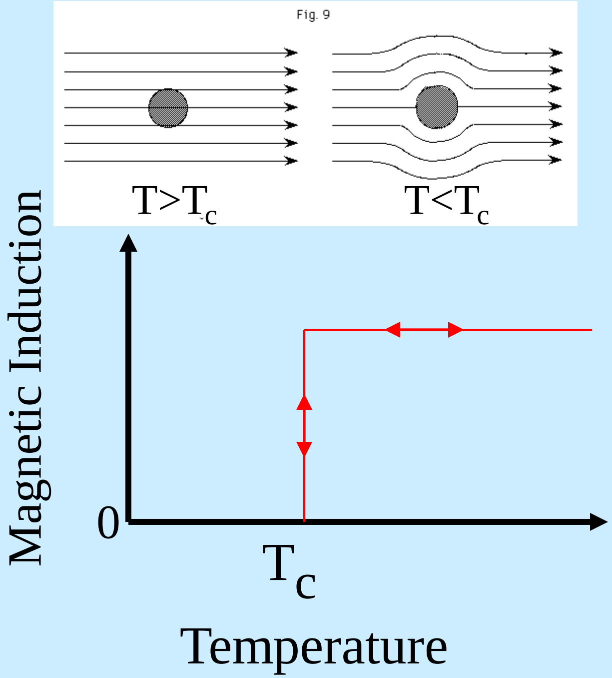
The Three Hallmarks of Superconductivity

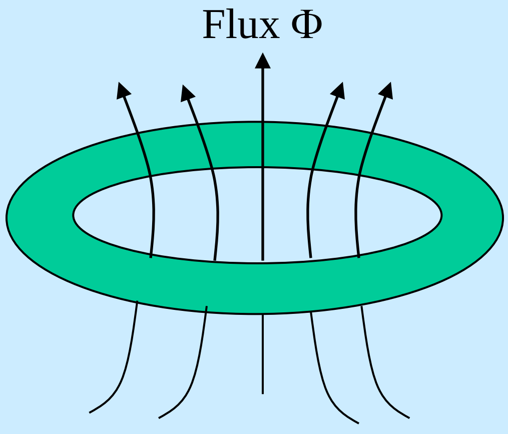
Zero Resistance



Complete Diamagnetism



Macroscopic Quantum Effects



Flux quantization $\Phi = n\Phi_0$
Josephson Effects

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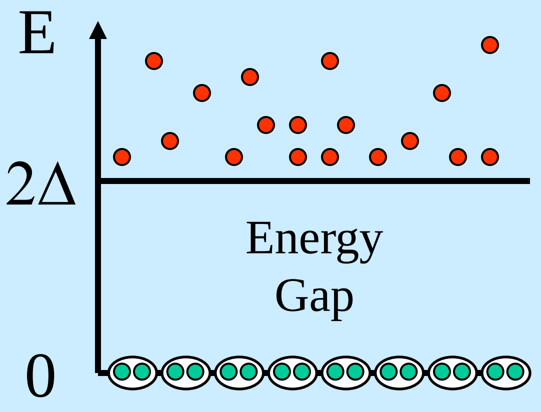
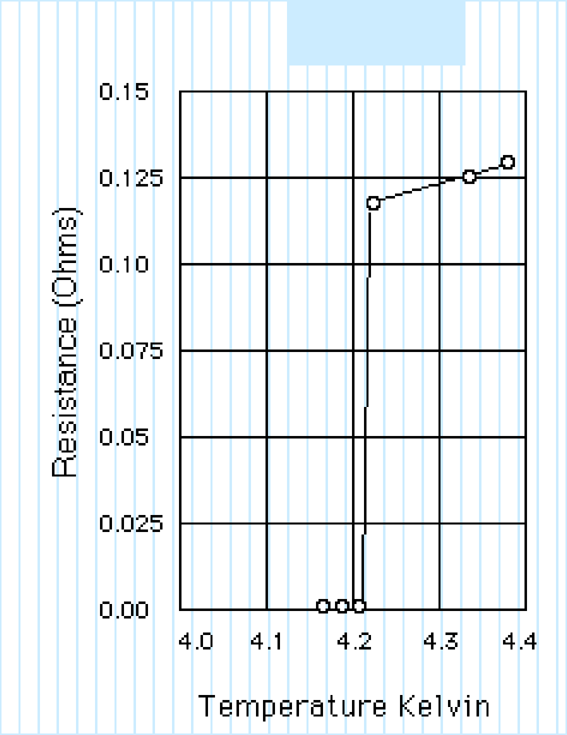
Zero Resistance

R = 0 only at ω = 0 (DC)

R > 0 for ω > 0





The Kamerlingh Onnes resistance measurement of mercury. At 4.15K the resistance suddenly dropped to zero

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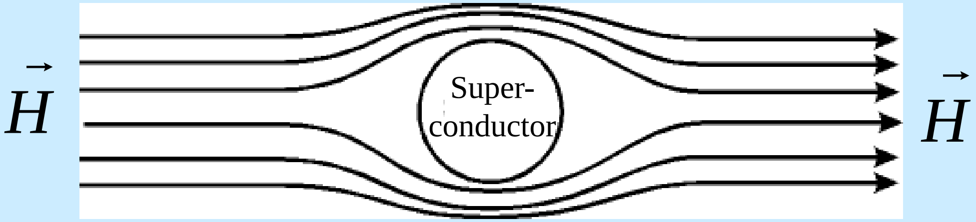
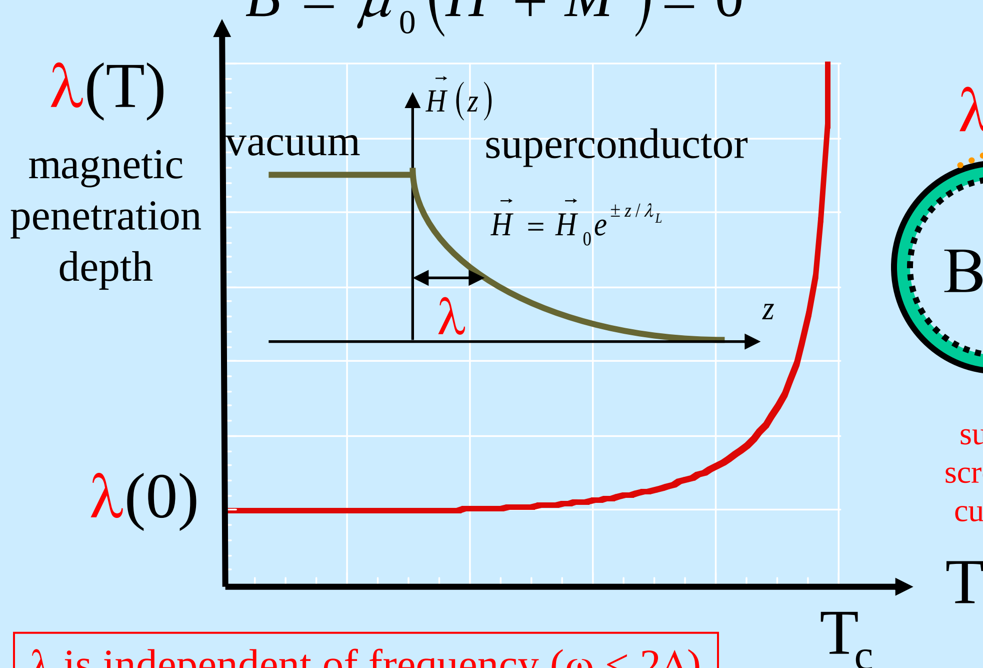
Perfect Diamagnetism

Magnetic Fields and Superconductors are not generally compatible

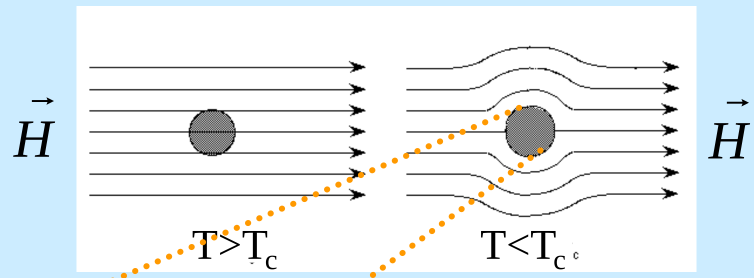


$$\vec{B} = \mu_0\left(\vec{H} + \vec{M}\right) = 0$$

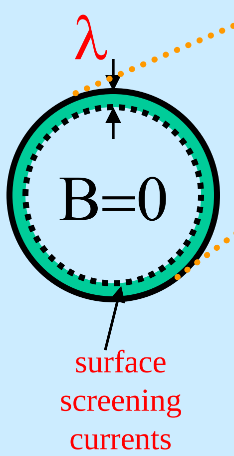


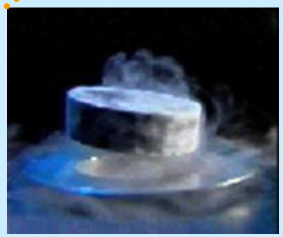
λ is independent of frequency (ω < 2Δ)

The Meissner Effect



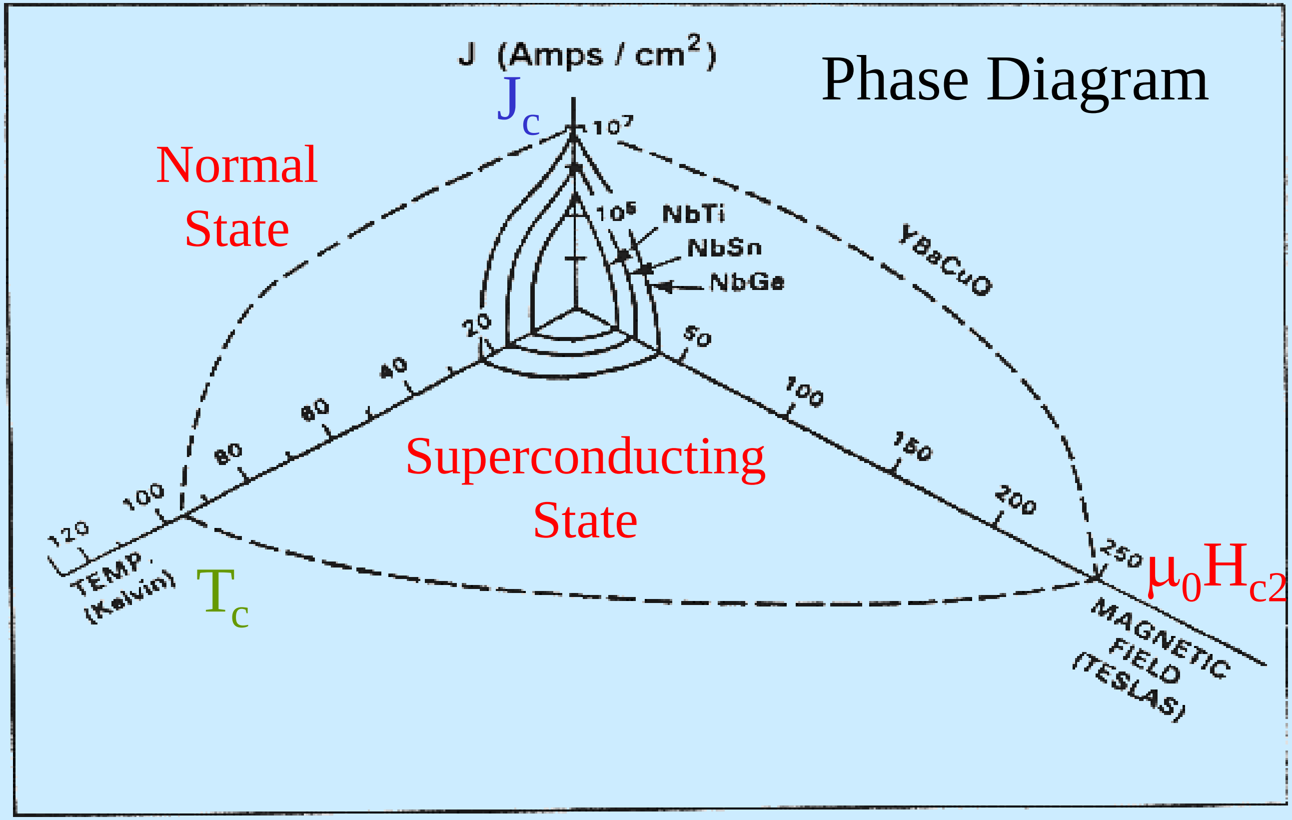
Spontaneous exclusion of magnetic flux





The Yamanashi MLX01 MagLev test vehicle achieved a speed of 343 mph (552 kph) on April 14, 1999

What are the Limits of Superconductivity?



$$f_{\text{super}} = f_{\text{normal}} + \alpha(T)|\psi|^2 + \frac{\beta(T)}{2}|\psi|^4 + \frac{1}{2m^*}\left|\left(\frac{\hbar}{i}\vec{\nabla} - e^*\vec{A}\right)\psi\right|^2 + \frac{\mu_0 h^2}{2}$$

Ginzburg-Landau free energy density

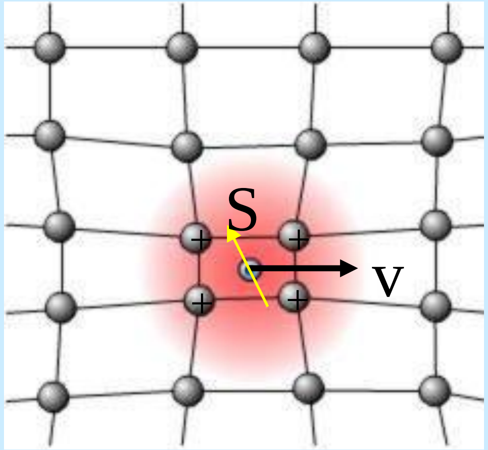
Temperature dependence

Currents

Applied magnetic field

BCS Theory of Superconductivity

Bardeen-Cooper-Schrieffer (BCS)

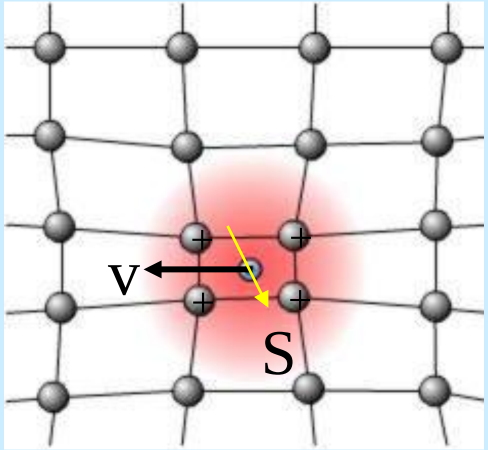


First electron polarizes the lattice

Cooper Pair

s-wave ($\ell = 0$) pairing

Spin singlet pair



Second electron is attracted to the concentration of positive charges left behind by the first electron

$$T_c \cong \Omega_{Debye} \ e^{-1/NV}$$

Ω_{Debye} is the characteristic phonon (lattice vibration) frequency
N is the electronic density of states at the Fermi Energy
V is the attractive electron-electron interaction

A many-electron quantum wavefunction Ψ made up of Cooper pairs is constructed with these properties:

An energy $2\Delta(T)$ is required to break a Cooper pair into two quasiparticles (roughly speaking)

Cooper pair size: $\xi = v_F \cdot \frac{\hbar}{\Delta}$

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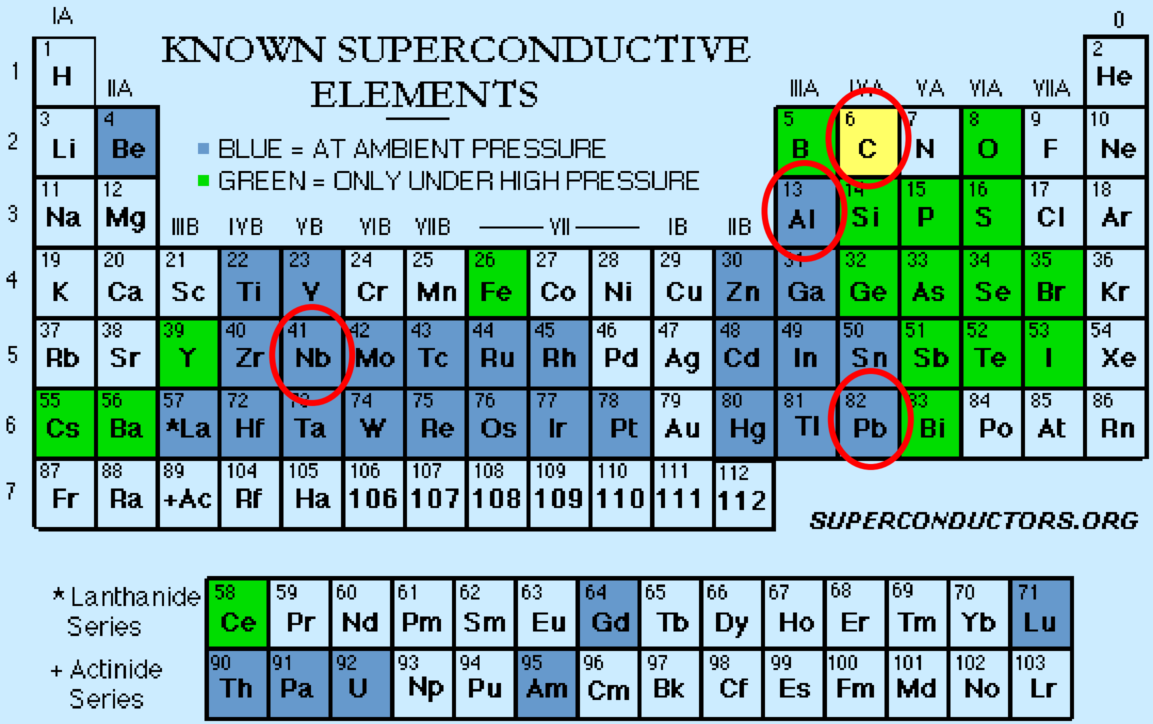
http://www.chemsoc.org/exemplarchem/entries/igrant/hightctheory_noflash.html

Where do we find Superconductors?



Also:

Nb-Ti, Nb_3Sn, A_3C_{60}, NbN, MgB_2, Organic Salts ($(TMTSF)_2X$, $(BEDT\text{-}TTF)_2X$), Oxides (Cu-O, Bi-O, Ru-O,…), Heavy Fermion (UPt_3, $CeCu_2Si_2$,…), Electric Field-Effect Superconductivity (C_{60}, $[CaCu_2O_3]_4$, plastic), …

Most of these materials, and their compounds, display spin-singlet pairing

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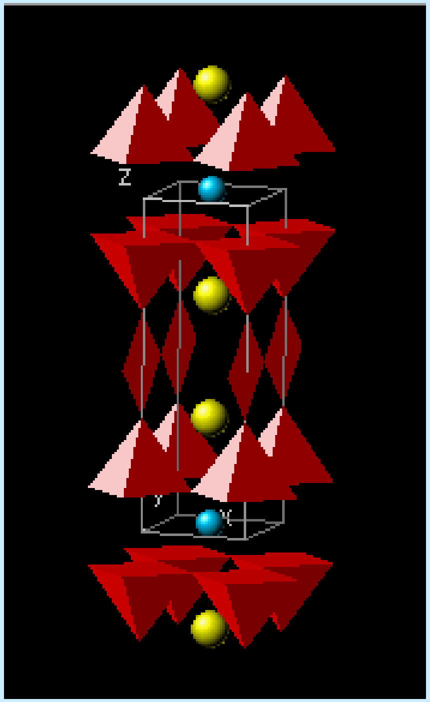
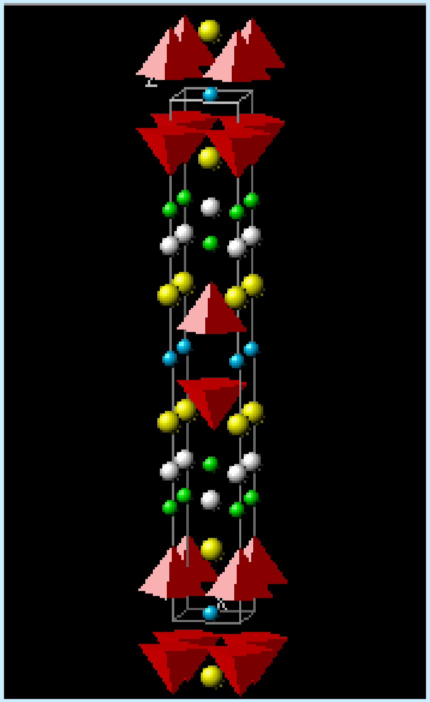
The High-T_c Cuprate Superconductors

Layered structure – quasi-two-dimensional
Anisotropic physical properties
Ceramic materials (brittle, poor ductility, etc.)
Oxygen content is critical for superconductivity

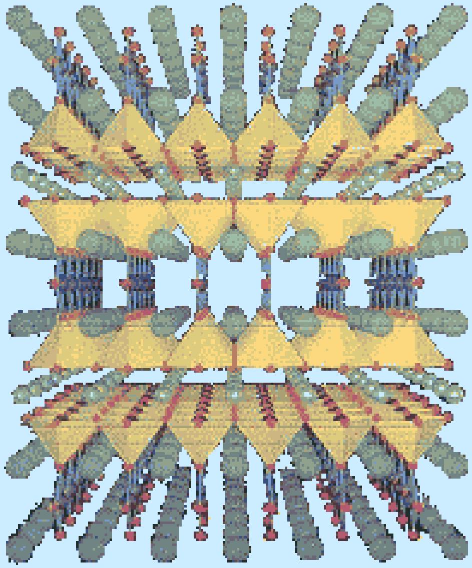
Spin singlet pairing
d-wave ($\ell = 2$) pairing



$YBa_2Cu_3O_{7-\delta}$



$Tl_2Ba_2CaCu_2O_8$



Two of the most widely-used HTS materials in applications