MTLE-6120: Advanced Electronic Properties of Materials

Superconductivity

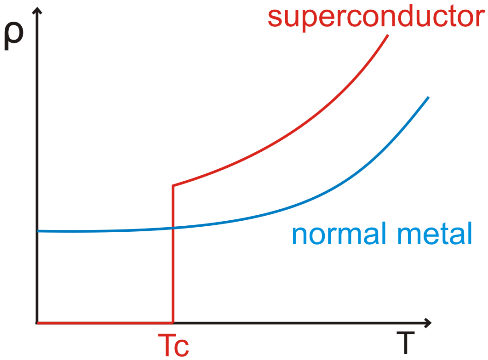
Contents:

- Phenomenology: resistance, Meissner effect, type I and II
- Microscopic origin of superconductivity
- High-T_c superconductivity

Reading:

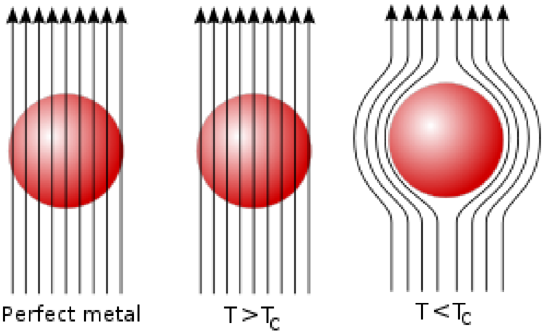
- Kasap: 8.9 - 8.10
- *Nature* **518**, 179 (2015) for high T_c

Zero resistance



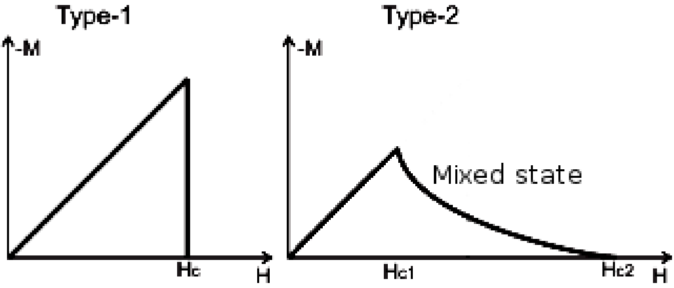
- Many metals exhibit zero resistance below a temperature T_c
- First discovered in 1911 in mercury ($T_c = 4.2$ K)
- Poorer conductors are usually better superconductors (higher T_c)
- Gold, copper and silver have negligible T_c
- Highest among pure metals: lead ($T_c = 7.2$ K) and niobium ($T_c = 9.3$ K)

Meissner effect



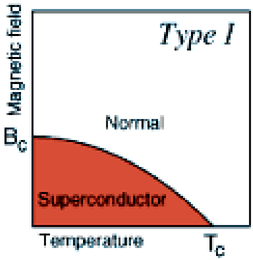
- Superconductor $\neq$ perfect conductor
- Perfect conductor permits magentic fields (like normal metal)
- Superconductor expels magentic field completely
- Meissner effect: perfect diamagnetism $\chi_m = -1$
- Typical paramagnetic or diamagnetic metals, $|\chi_m| \sim 10^{-6} - 10^{-4}$

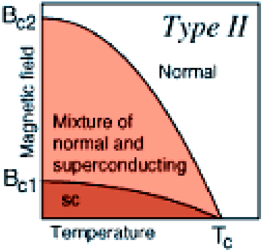
Critical fields

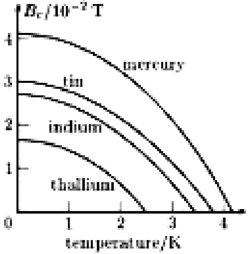


- Perfect diamagnet up to a maximum field H_c
- Two types of behavior possible beyond H_c
- Type I: Abrupt transition to normal state $\rho \neq 0$, $\chi_m \sim 0$
- Type II: gradual reduction of $|\chi_m| \to 0$ (with $\rho = 0$)
- Mixed state of $\rho = 0$ and $\chi_m > -1$ ranges from lower critical field H_{c1} to upper critical field H_{c2}

Critical fields: T dependence

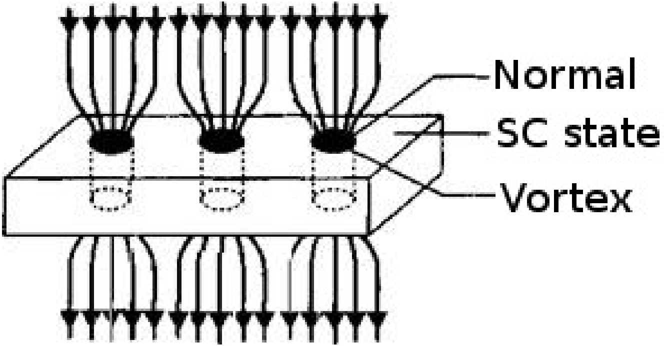






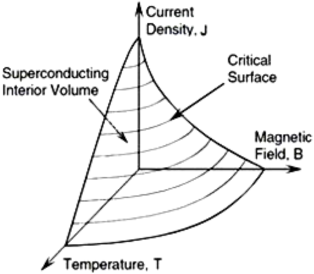
- Critical field decreases with temperature (exactly like ferromagnets)
- Higher critical field correlated with higher T_c
- Upper and lower critical fields vanish together at T_c for type II (no T_{c1} and T_{c2})

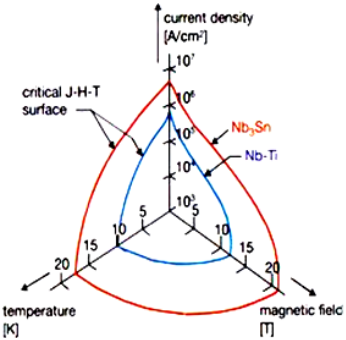
Mixed state: vortices



- Field enters superconductor in domains: vortices
- Normal state inside, and superconducting (SC) state outside
- Quantum of flux $\Phi_0 = \frac{h}{2e} \approx 2 \times 10^{-15}$ Tm^2 in each vortex
- Increasing density of vortices between H_{c1} and H_{c2}
- At H_{c2}, no SC region left $\Rightarrow \rho \neq 0$

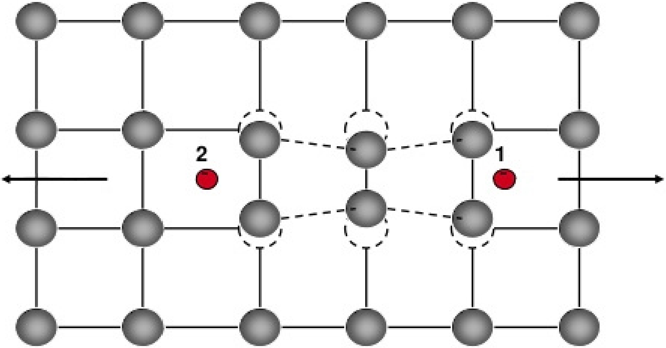
Critical current





- Beyond current density j_c, switch to normal state
- Primary application of superconductors: high-field magnets
- T, j and H (B) all push SC to normal state
- Limiting magnet performance limited by critical surface
- For metals and alloys, j_c and H_c increase with T_c
- Not generally true for high-T_c materials

Microscopic origins: e-ph interactions



- One electron distorts the lattice (emits / absorbs a phonon)
- This distortion reduces potential for second electron
- Attractive electron-electron interaction mediated by phonons
- Attraction $-\Delta$ between electrons at $k\uparrow$ and $-k\downarrow$
- All electrons near Fermi surface in Coooper pairs with energy reduced by Δ
- Result: band gap Δ near Fermi surface: no free electrons

Microscopic origins: BCS theory

- Attraction produces band gap Δ
- But, pairs behave like spin zero particles with net charge $2e$
- Bosons: all pairs in same quantum state for $T < T_c$
- Apply field, all pairs carry current together (coherently)
- Gap $\Delta \Rightarrow$ no states to scatter into!
- Perfect conductor *because* of gap!
- Facilitated by e-ph interactions $\Rightarrow$ resistive metals are better superconductors!
- Increase temperature: pairs break thermally (T_c)
- Increase magentic field: imbalance in spin energies breaks pair (H_c)
- Increase current density: pairs have enough momentum to scatter against electrons (j_c)

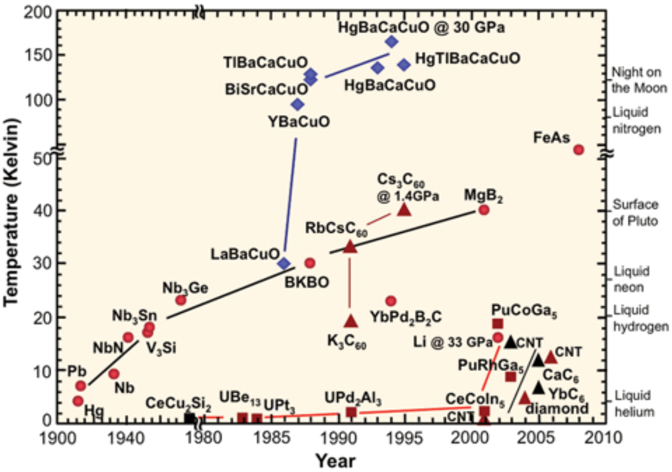
Microscopic origins: Type I vs Type II

Two important length scales in superconductors

1. Coherence length ξ: length scale of the quantum wavefunction variation
2. Penetration depth λ: length scale of magnetic field variation

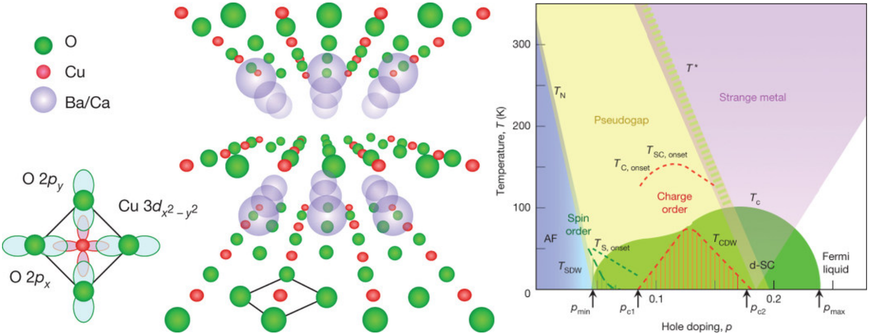
- When $\xi > \lambda$, cost of breaking wavefunction higher:
  stay SC till pairs break (Type I)
- When $\xi < \lambda$, break wavefunction to relax magnetic field energy
  $\Rightarrow$ favorable to form vortices (Type II)
- Vortex: normal state extent $\sim \xi$ surrounded by field region $\sim \lambda$

T_c versus time



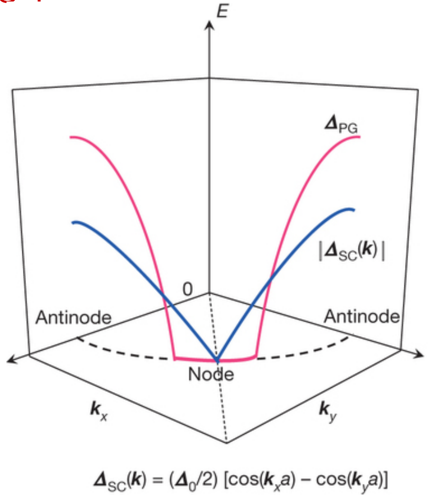
- Conventional metals with $T_c < 10$ K and alloys with $T_c < 40$ K
- New classes of materials with T_c approaching 160 K!

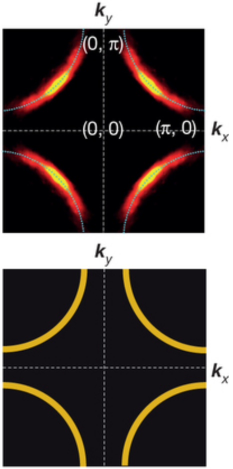
Typical phase diagram of cuprate superconductors



- Correlated-electron materials: many poorly understood phases!
- Antiferromagnetism, spin-density waves and strange metals
- Strange metal: resistivity $\propto T$ even when $\lambda < a$
- d-wave superconductor: pairs have $l = 2$ instead of $l = 0$ (BCS)

Psuedogap: Fermi surface arcs





- No real superconducting gap Δ
- Anisotropic gap in states with zero gap in certain directions
- Angular dependence of gap like a d-orbital
- Read *Nature* **518**, 179 (2015) for more!