561 Fall 2005 Lecture 18

Superconductivity: Experimental Facts, Electrodynamics References: Phillips, Sec. 11.1
Tinkham, "Intro. to Superconductivity", Ch 1 (Good summary in Ch. 1)
de Gennes, "Superconductivity of Metals and Alloys", Ch. 1,2,3(p48-65)

1. Facts about Superconductivity

- Discovery - K. Onnes (1911)
- Resistance = 0 to great precision
- Meisner Effect (1933) - field expelled from bulk up to a critical field H_c; reversible for small fields $H < H_c$
- Two types of superconductors: I, II Two critical fields in Type II
- A *very small change in free energy* in the superconducting state as demonstrated by the energy of magnetic field that destroys the phase
- Absence of low energy electronic excitations: complete absence in Type I superconductors as demonstrated by the specific heat, but this is not essential for superconductivity since it does not always happen
- Macroscopic phase coherence - flux quantization and Josephson effect (discovered later - 1962)
- Isotope effect - demonstrated in 1950

2. Nature of the Superconducting State

- The Superconducting State is a new stable phase of matter. There must be an order parameter that is not readily detected by x-rays or other experiments that would detect some structural order
- Must be a quantum mechanical effect - theorem in classical mechanics that a magnetic field cannot change the free energy of a system
- Must have coupling of the order parameter to macroscopic electrodynamics to describe the properties of this state of matter
- A successful macroscopic theory must:
  - Involve a collective behavior of the electrons which leads to a new order parameter (analogous to magnetism, ..., but different!)
  - Be robust – i.e., it must show how tiny correlation energies among the electrons can stabilize the superconducting state, even in the presence of MUCH larger correlation energies among the electrons. How can one make a theory to describe such small effects when we cannot calculate the big effects to an accuracy anywhere close to the small energies involved in superconductivity?

- Involve phonons in some way – it must involve the dynamical motions of the nuclei, i.e. the *velocities* – a breakdown of the adiabatic approximation

3. Free Energy

- relation to H_c
- Magnitude of $F_S - F_N$ extremely small $\approx 10^{-6}$ eV/electron

4. Electrodynamics

- London theory; London length λ_L (theory of magnetic penetration based solely on electromagnetic theory, no quantum mechanics)
  $\nabla^2 h = \frac{1}{\lambda_L^2} h$; $\lambda_L^2 = \frac{mc^2}{4\pi n_s e^2}$
- Pippard non-local generalization; coherence length ξ, $\xi_0 \equiv \xi(T = 0) \approx \frac{\hbar v_F}{\pi \Delta}$, where $\Delta \approx k_B T_c$ is a characteristic energy

5. Two types of Superconductors

- Type I (Pippard): $\xi >> \lambda$
- Type II (London): $\xi << \lambda$
- M vs. H for Type I and Type II
- Vortices; Flux Quanta: $\Phi_0 = \frac{hc}{2e}$
- Special nature of interface energy between normal and superconducting states that leads to flux penetration with and many small normal regions as possible
- Flux Lattice (Abrikosov)
- Additional points
  The flux penetration in type II leads to resistance - vanishes only because flux are pinned by impurities
  Flux penetration is what makes possible NMR is superconductors!

6. Macroscopic phase coherence - return to this subject later

- Multiply-connected topology of a superconductor
- Quantum order parameter extends over macroscopic distances
- Flux quantization implies persistent currents
- The value of the flux quantum $\Phi_0 = \frac{hc}{2e}$ is the direct evidence that pairs are involved (as in the BCS theory) – Example of topological constraint that leads to precise quantization even in a messy, imperfect material