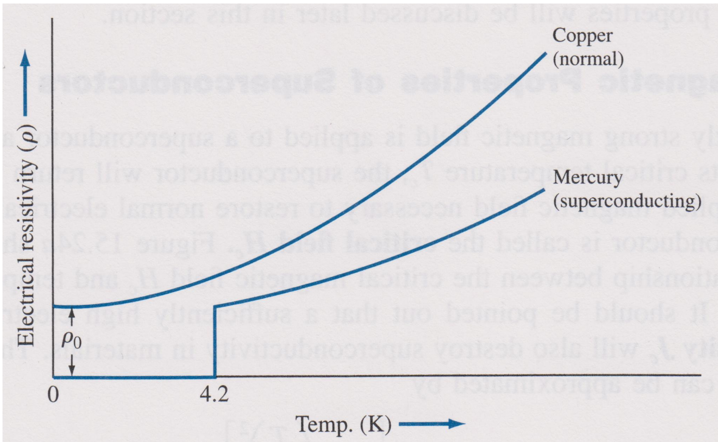
PHYSICS 2800 – 2nd TERM
Outline Notes (continued)

Section 5. Superconductors (see also textbook section 15.8)

Superconductivity (SC) is concerned with the low-T behaviour of the electrical conductivity σ or the resistivity ρ (= $1/\sigma$), which occurs in just a few specific materials.

5.1 Overview

In 1911 it was discovered that for $T < 4$ K a sample of Hg has zero ρ (or infinite σ). Soon the SC effect was discovered in other materials, mainly metals, below some critical temperature T_C.
(see also figure below).



Schematic T-dependence of the electrical resistivity for a normal metal (Cu) compared to that of a superconductive metal (Hg) in the vicinity of 0 K.

In metals, T_C ranges from a fraction of 1 K up to ~10 K.
In metallic alloys, higher T_C values up to ~25 K can be obtained.

This is how it remained for many years (and in fact it was believed that ~30 K was an upper limit on T_C).

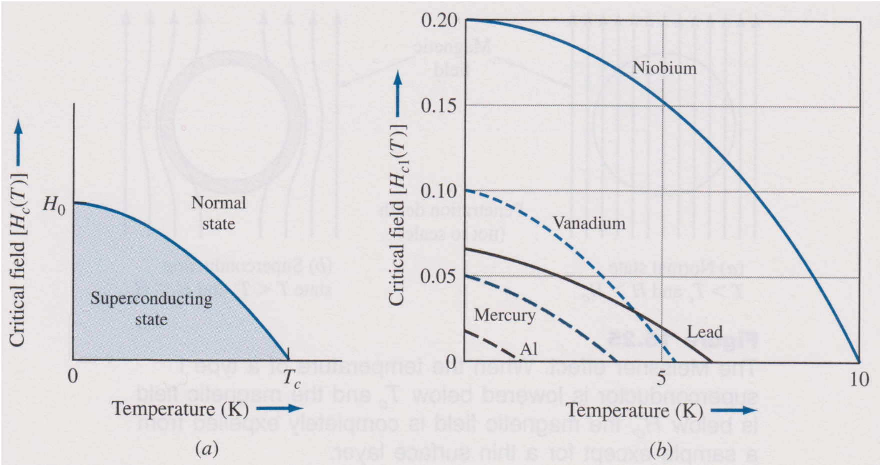
Then in 1986 a new class of SC was discovered in some particular ceramic materials, such as $YBa_2Cu_3O_7$ (with $T_C = 90$ K).
Remarkably, T_C values up to ~100 K or even 200 K were soon obtained. This opened up the potential for practical applications of superconductivity because the T_C values were above liquid nitrogen temperatures (boiling point 77 K), which is an inexpensive coolant.

In the conventional SCs (metals, alloys) the $\rho = 0$ property is very well tested (e.g., by observing currents in SC loops remaining undiminished over large periods of time).

5.2 Magnetic field effects

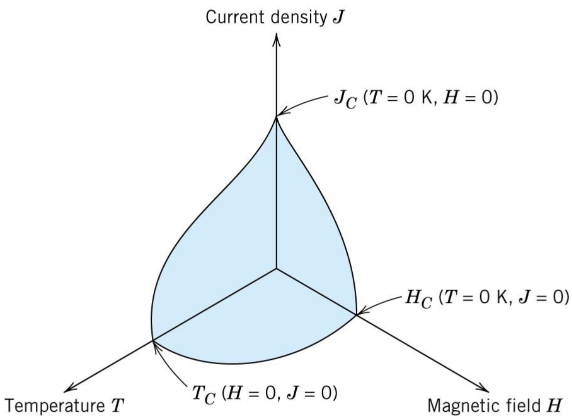
Experimentally, it was found that the T_C values were reduced by *either* applying a large field H *or* making a large current density J pass through the material.
For large enough H or J (exceeding some critical values) the SC property can be destroyed.

Considering first the effect of H:-



Critical field *vs*. T for
(a) general case,
(b) examples of several SC materials.

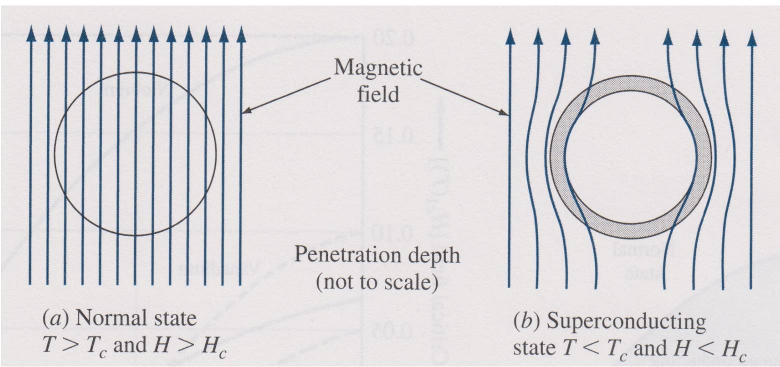
An applied current has the same effect giving rise to the following type of behavior:-



Schematic 3D plot of T_C *vs*. current density and magnetic field, showing the surface separating the superconducting and normal states.

The occurrence of SC is closely related to a particular magnetic behaviour called the Meissner effect

– the field lines of B are excluded (expelled) from the interior of the SC material, except in a very thin surface layer.



Representation of the Meissner effect. While in a SC state, a body of material (circular region) excludes a magnetic B field from its interior, except for a small distance (called the penetration depth) near the surface.

But $\quad B = \mu_0 (H + M)$ or $B = \mu_0 \mu_r H = \mu_0 (1 + \chi_m) H$,

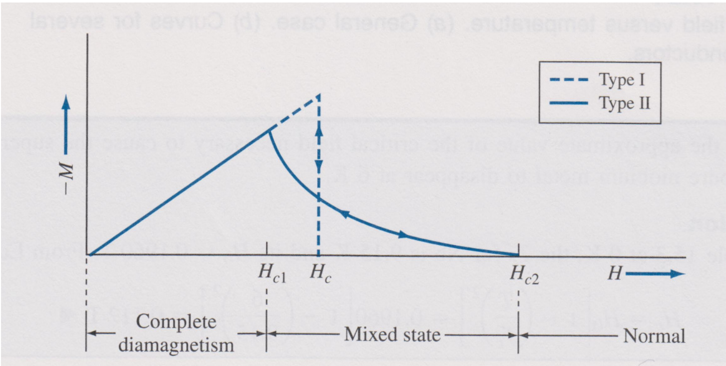
so $\quad B = 0$ implies $M = -H$ or $\chi_m = -1$, i.e., the SC is like a "perfect" diamagnet.

The above property holds only for $H < H_C$.
In some materials there is just one H_C value

– these are called Type I SC.

In other materials there are two values H_{C1} and H_{C2}, such that for $H < H_{C1}$ the Meissner effect is complete ($B = 0$), but for $H_{C1} < H < H_{C2}$ there is a partial Meissner effect in which the B field is partially excluded from the SC (and so $-1 < \chi_m < 0$)

– these are called Type II SC.



Magnetization *vs*. H curves for ideal Type I and Type II SC materials. The Type II SCs are partially penetrated by the B field for H between H_{C1} and H_{C2}.

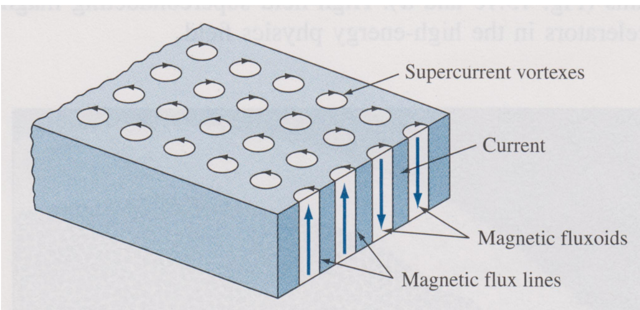
Some T_C values for selected metals, intermetallic and ceramic compound SCs:

Metals	T_c (K)	H_0* (T)	Intermetallic compounds	T_c (K)	Ceramic compounds	T_c (K)
Niobium, Nb	9.15	0.1960	Nb_3Ge	23.2	$Tl_2Ba_2Ca_2Cu_3O_x$	122
Vanadium, V	5.30	0.1020	Nb_3Sn	21	$YBa_2Cu_3O_{7-x}$	90
Tantalum, Ta	4.48	0.0830	Nb_3Al	17.5	$Ba_{1-x}K_xBiO_{3-y}$	30
Titanium, Ti	0.39	0.0100	NbTi	9.5		
Tin	3.72	0.0306				

*H_0 = critical field in teslas (T) at 0 K.

Examples of Type I SC materials are Hg, Pb and Sn; examples of Type II SC materials are Nb, NbTi and Nb_3Sb.

On a microscopic level, in a Type II SC when $H_{C1} < H < H_{C2}$, the B field penetrates the material in the form of individual cylindrical tubes. A "supercurrent vortex" flows around each tube, inside which B is nonzero and is quantized (known as a "fluxoid").



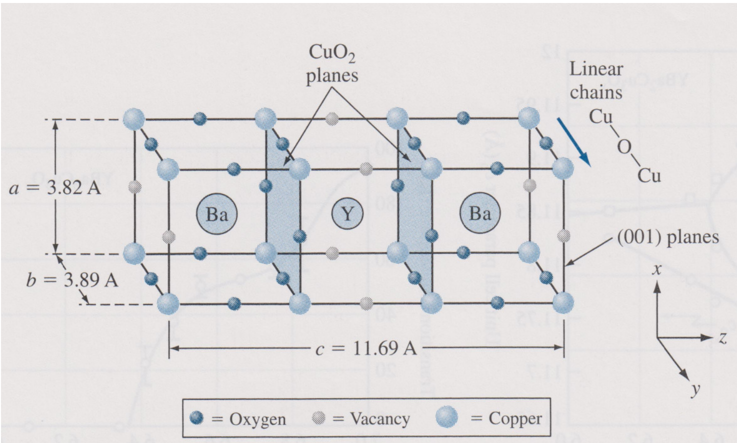
Schematic figure of magnetic fluxoids in a Type II SC when $H_{C1} < H < H_{C2}$.

When H is increased to H_{C2} the fluxoids all collapse and the material becomes a normal material.

5.3 Theories of SC

Why does SC occur? A successful theory was developed in the 1950s by Bardeen, Cooper and Schrieffer (called the BCS theory).
It depended on identifying an *attractive* component to the interaction forces between two electrons inside the SC (in addition to the Coulomb force of repulsion). This could come about from the distortion effect on the crystal lattice (involving the atomic vibrations or phonons). In some circumstances the electrons could then move as pairs (with opposite value of the spin) through the material, giving rise to the SC effect.

The new ceramic-based SC compounds, discovered in 1986, have a much higher T_C (~ 100 to 200 K). It is believed that an electron-pairing effect still takes place, but it must occur in quite a different way from the original BCS theory.



Idealized $YBa_2Cu_3O_7$ orthorhombic crystal structure. Note the location of the CuO_2 planes.

5.4 Applications of SC

For "conventional" SCs, the most important for present technology, because of their relatively high critical fields, are Nb (Type I with T_C ~ 9 K and H_C ~ 0.2 T) and Nb_3Sn (Type II with T_C ~ 21 K and H_{C2} ~ 22 T), e.g., in power transmission cables, magnetic levitation in transportation, powerful SC electromagnets for magnetic resonance imaging (or MRI), etc. NbTi alloys (Type II with T_C ~ 9 K and H_{C2} ~ 11 T) are also widely used, in spite of the lower T_C, because H_{C2} is still large and the alloy is more convenient for manufacturing processes.

As mentioned earlier, an important factor for applications involving the high-T_C SC materials is that the T_C values are above liquid-N_2 temperatures (~ 77 K). On the other hand, they tend to be brittle and it is hard to eliminate materials defects. So far, the applications have mainly been as thin film devices in (e.g.) high-speed parallel computers.