# FoP 3B Part II

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## Lecture 7: Introduction to Superconductors

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## Aim of today's lecture

► What are the characteristic features of superconductivity?

*Key concepts:*

-Critical temperature (superconductivity as a phase transition)

-Meissner effect (leading to diamagnetism)

-Critical magnetic fields- Type I vs Type II superconductors

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# Resistivity vs temperature for a metal

$$\rho(T) = \rho_o + aT^2 + bT^5$$

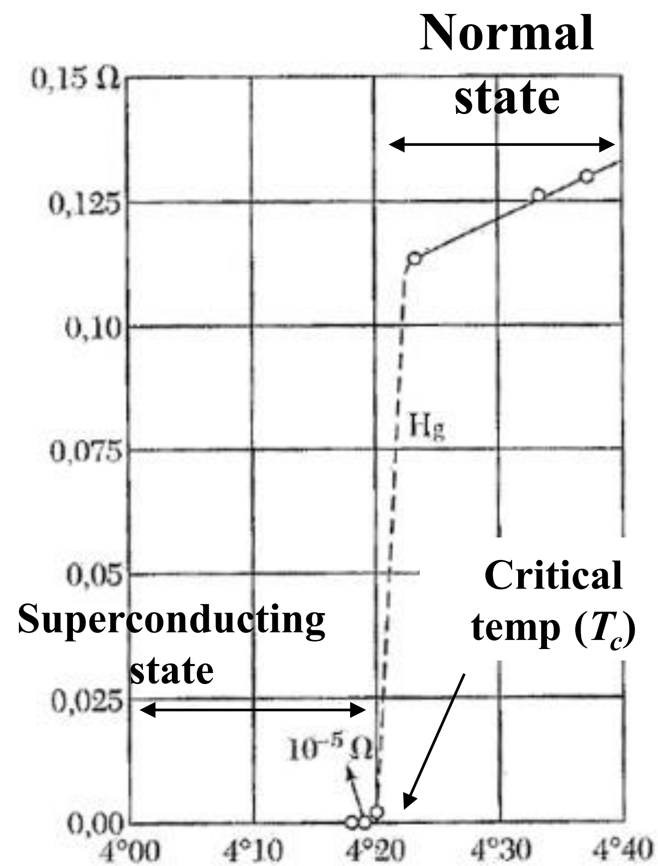
Impurity effects

electron-electron scattering

electron-phonon scattering

- Below critical temp ($T_c$) resistivity suddenly drops to zero.
- Abrupt change implies a phase transition, i.e. superconductivity is a new form of matter.

Kammerling Onnes measurement on Hg (1911) ⇒

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# Examples of superconducting materials

| | Substance | $T_c$ (K) | |
|---|---|---|---|
| | Al | 1.2 | |
| | Hg | 4.1 | First superconductor, discovered 1911 |
| | Nb | 9.3 | Highest $T_c$ of an element at normal pressure |
| | Pb | 7.2 | |
| Elemental superconductors | Sn | 3.7 | |
| | Ti | 0.39 | |
| | Tl | 2.4 | |
| | V | 5.3 | |
| | W | 0.01 | |
| | Zn | 0.88 | |
| | Zr | 0.65 | |
| | Fe | 2 | High pressure |
| Superconductivity under high pressure | H | 300 | Predicted, under high pressure |
| | O | 30 | High pressure, maximum $T_c$ of any element |
| | S | 10 | High pressure |
| Used in superconducting magnets | $Nb_3Ge$ | 23 | A15 structure, highest known $T_c$ before 1986 |
| | $Ba_{1-x}Pb_xBiO_3$ | 12 | First perovskite oxide structure |
| | $La_{2-x}Ba_xCuO_4$ | 35 | First high $T_c$ superconductor |
| 'High' $T_c$ cuprates | $YBa_2Cu_3O_{7-\delta}$ | 92 | First superconductor above 77 K |
| | $HgBa_2Ca_2Cu_3O_{8+\delta}$ | 135–165 | Highest $T_c$ ever recorded |
| | $K_3C_{60}$ | 30 | Fullerene molecules |
| | $YNi_2B_2C$ | 17 | Borocarbide superconductor |
| | $MgB_2$ | 38 | Discovery announced in January 2001 |
| | $Sr_2RuO_4$ | 1.5 | Possible $p$-wave superconductor |
| | $UPt_3$ | 0.5 | "Heavy fermion" exotic superconductor |
| | $(TMTSF)_2ClO_4$ | 1.2 | Organic molecular superconductor |
| | ET-BEDT | 12 | Organic molecular superconductor |

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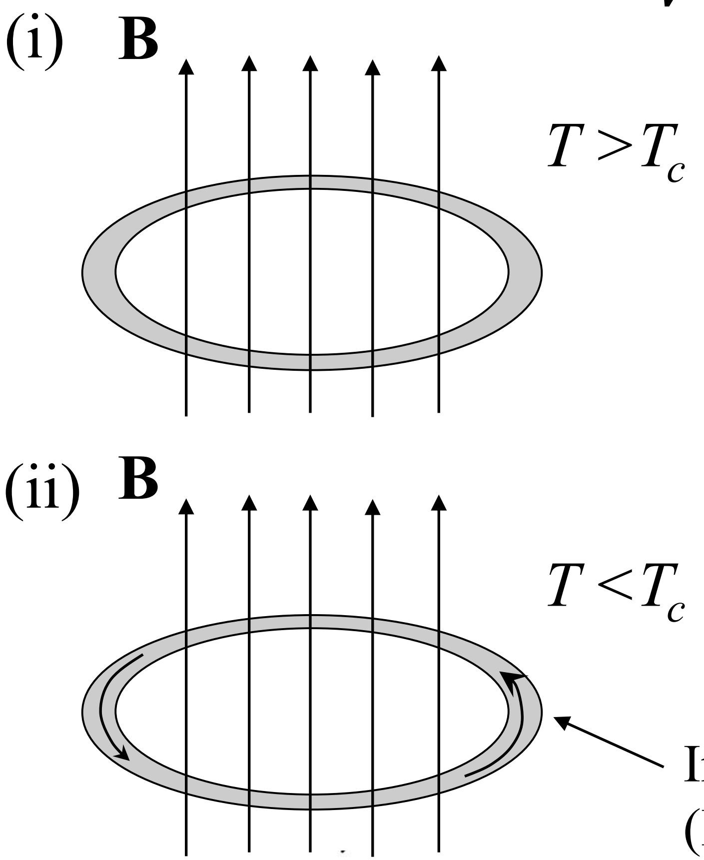
# Persistent currents (I)- is the resistivity really zero?

From $\mathbf{J} = \sigma \mathcal{E}$ electric field within a superconductor must be zero for constant current.

Applying Faraday's law of induction:

$$\vec{\nabla} \times \vec{\mathcal{E}} = -\frac{\partial \mathbf{B}}{\partial t} = 0$$




- Immerse metal ring in magnetic field at $T > T_c$.
- Cool to below $T_c$ and switch magnetic field off.
- Persistent current induced in superconductor (to maintain constant magnetic flux through the ring).

# Persistent currents (II)- is the resistivity really zero?

Decay of current density given by:

$$J(t) = J_o \exp(-t/\tau)$$

$\tau$ = average time between scattering events.

For a metal $\tau \sim 10^{-13}$ s, i.e. current decays to 1% its starting value within 1 picosecond.

For superconductors no noticeable decay in current even after several years $\Rightarrow$ resistivity less than $10^{-25}$ $\Omega$m (resistivity of Cu $\sim 10^{-8}$ $\Omega$m)

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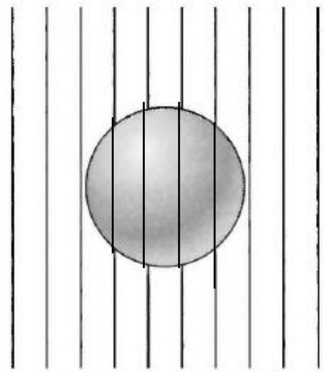
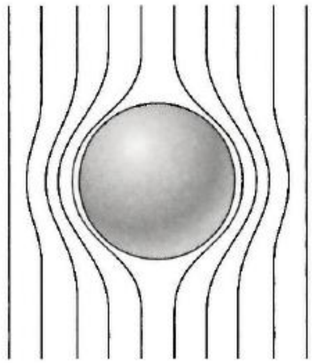
# Meissner effect (perfect diamagnetism)



$T > T_c$
(Normal state; paramagnet)



$T < T_c$
(Superconductor; diamagnet)

**B** = 0 in superconducting state. From $\mathbf{B} = \mu_o(\mathbf{H}+\mathbf{M})$:

$$\chi = \frac{M}{H} = -1$$

Magnetic susceptibility

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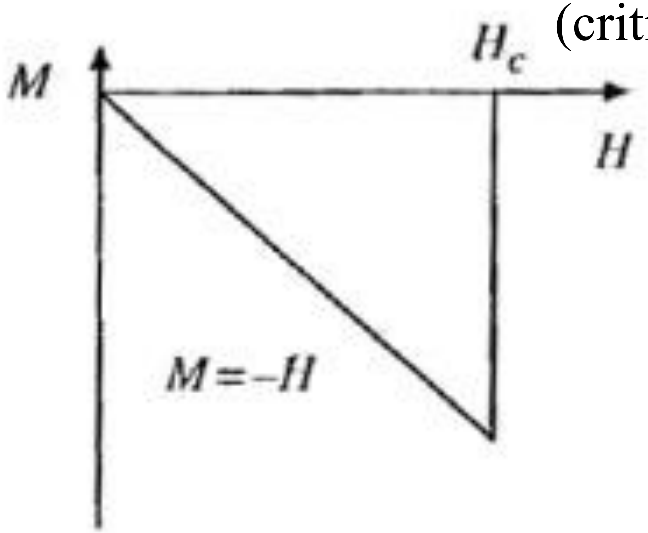
* Demo during lecture

# Type I vs Type II superconductors

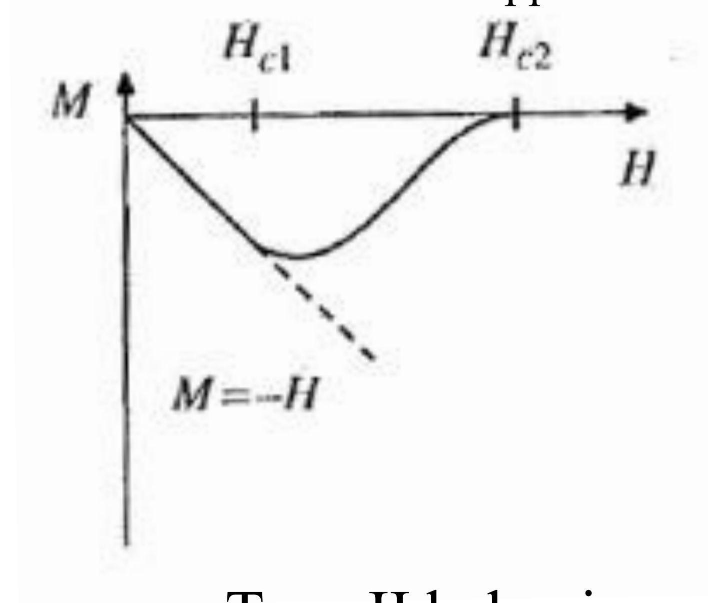
(critical $H$-field)




Type I behaviour

lower critical $H$-field

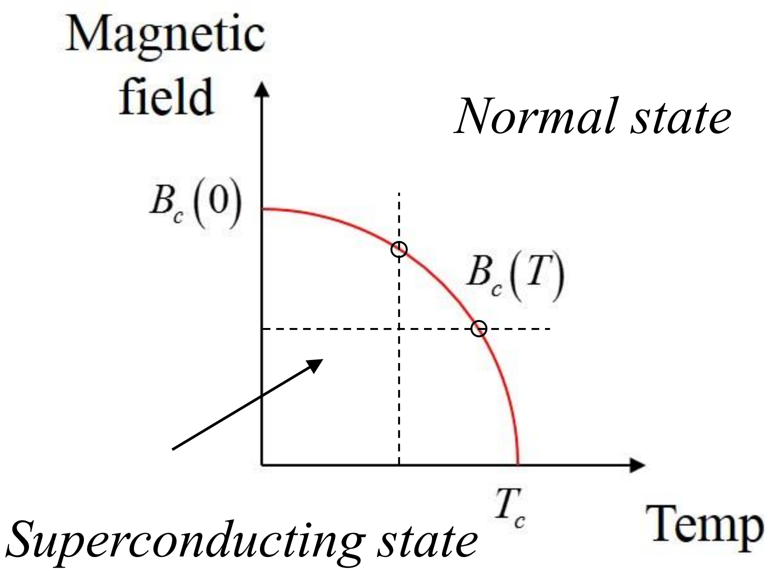
upper critical $H$-field




Type II behaviour

- Strong magnetic fields destroy superconductivity.
- For Type I the transition from superconducting to normal state is at a single critical field. In Type II a ‘mixed’ (or ‘vortex’) state exists between a lower and upper critical field.

# Type I superconductors



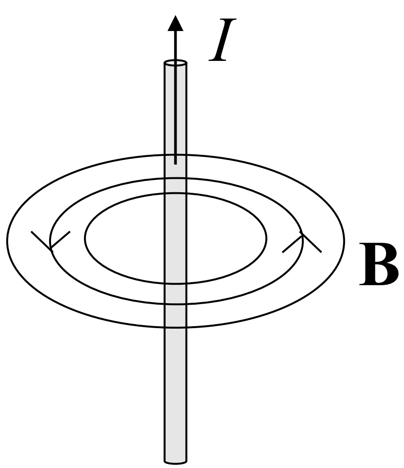

Critical field at a given temp:

$$\boxed{B_c(T) = B_c(0)\left[1 - \left(\frac{T}{T_c}\right)^2\right]}$$

<u>Implications for a current carrying wire</u>

Magnetic field for wire of radius $R$ :

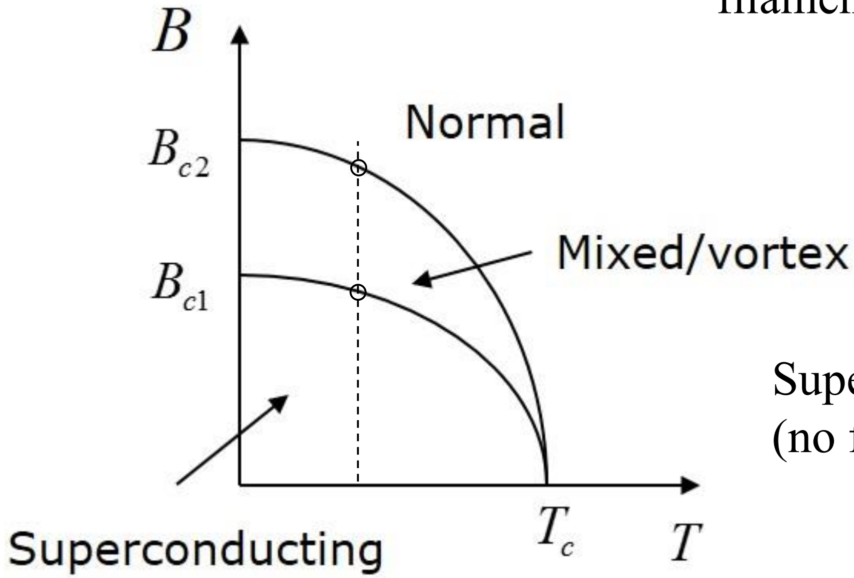
$$B = \frac{\mu_o I}{2\pi R} \qquad \text{(Ampere's law)}$$

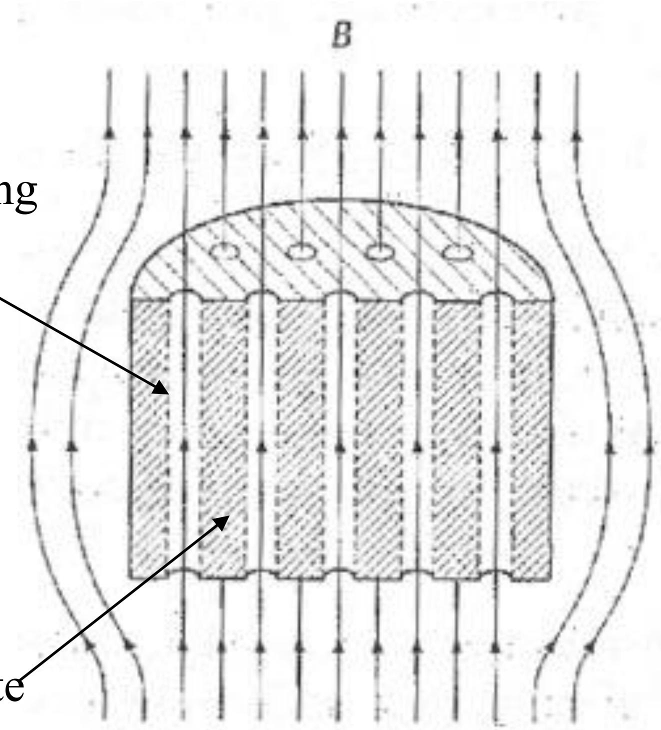



$\therefore$ Max allowed current:

$$\boxed{I_{max} = \frac{2\pi R B_c(T)}{\mu_o}}$$

# Type II superconductors




Magnetic field penetrating through Normal state 'filaments'

Superconducting state (no field penetration)

Experimental micrograph of mixed state (ferromagnetic powder exposes filaments)