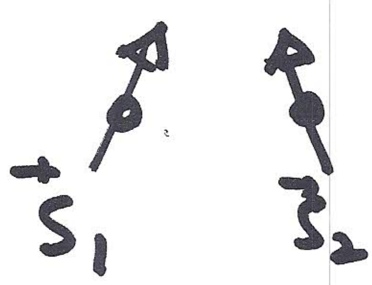
ORIGIN OF B_E

Simple model: Heisenberg model



Interaction energy

$$U = -2J\,\vec{S}_1 \cdot \vec{S}_2$$

↑ convention

$\underline{J > 0}$: ↑ ↑ has lower energy than ↑↓

(Ferromagnetic coupling)

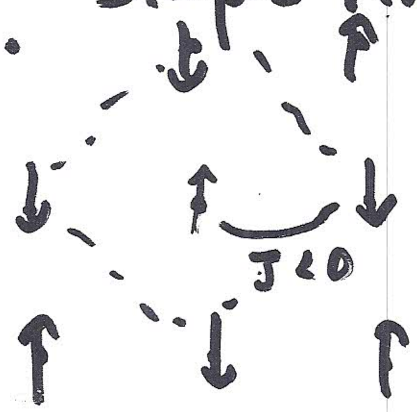
$J < 0$ ↑↓ has lower energy

(Antiferromag. coupling)

$J > 0$: $B_E = +\lambda M_a$ ↑B_a ↑B_E

$J < 0$: $B_E = -\lambda M_a$ ↑B_a ↓B_E

Simple Antiferromagnet



$T=0$: 2-Sublattice A & B Model.

⇒

what does expt. say?

How large is B_E?

$$B_E \doteq \lambda M_s \quad : \quad \lambda = \frac{T_c}{C} \quad : \quad C = \frac{N g_J^2 J(J+1)}{3k_B}\mu_B^2$$

<u>**Iron**</u>

Take: $J = S$; $S = 1$, $g_J = 2$ (spin only)

N = # of moments/volume

M_s = mag. moment/volume

$T_c \simeq 1000$ K

<u>UNITS:</u> (CGS) easy

$$[\lambda] : \frac{3k_B T_c}{N g_J^2 J(J+1)\mu_B^2} : \frac{\text{erg}}{\frac{1}{\text{cm}^3}\cdot\left(\frac{\text{erg}}{\text{gauss}}\right)^2} = \frac{(\text{gauss})^2}{\text{erg}}\cdot\text{cm}^3$$

$$M_s = N\mu_B : \frac{1}{\text{cm}^3}\cdot\frac{\text{erg}}{\text{gauss}}$$

$$\therefore \boxed{[\lambda M_s] = \text{gauss}} \; - \text{G}$$

$\lambda \approx 5000$, $M_s \approx 1700$

$$\lambda M_s \cong 10^7\,\text{G} = 10^4\,\text{KG} = 10^3\,\text{T}$$

Huge field

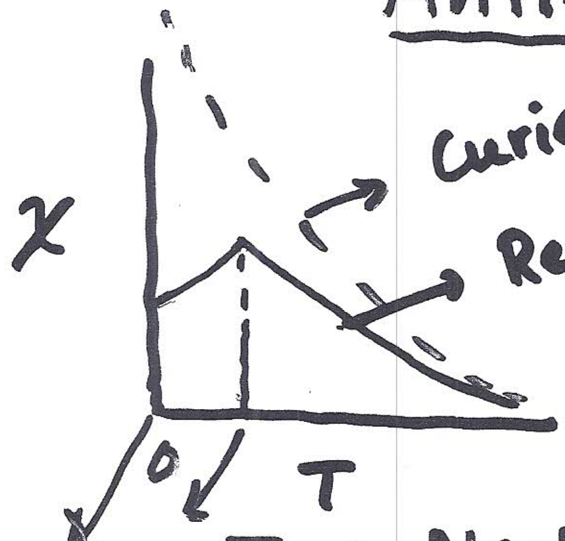
Dipole

Dipole

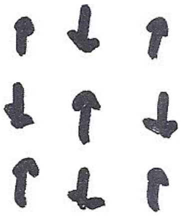
TOO small

If $T_c \sim 10$ K: $\cancel{\lambda M_s}$ $B_E \sim 10^2$ KG (still large)

Antiferromagnet (AFM)



T_N : Neel Temperature



$$T \gg T_N : \chi_{tot} \cong \frac{C}{T+T_N}$$

(No divergence in χ_{tot} as seen in FM)

Simple theory:

$$M_A = \chi(B_a - \overbrace{\lambda M_B}^{B_E}) \qquad \chi = \frac{C}{T} \leftarrow \text{single spin}$$

$$M_B = \chi(B_a - \lambda M_A)$$

$$M_A = \chi B_a - \chi\lambda\left[\chi B_a - \chi\lambda M_A\right]$$

$$M_A(1-\chi^2\lambda^2) = \chi(1-\lambda\chi)B_a$$

$$M_A = \frac{\chi(1-\lambda\chi)}{1-\chi^2\lambda^2}B_a = \frac{\chi}{1+\chi\lambda}B_A$$

$$\boxed{T_N = \lambda C}$$

$$M_A = \frac{C/T}{1+C\lambda/T}B_A = \frac{C}{T \underset{\frown}{+} T_N}B_A$$

+ Sign

SUPERCONDUCTIVITY

Chapter 10 (8^{th} edition)

Only Experimental Survey (pages 259 - 269)

For the Final Exam.

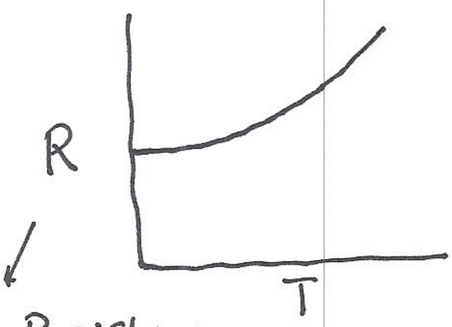
A new phenomena when discovered in 1911

(Kamerlingh Onnes in Leiden, Holland)

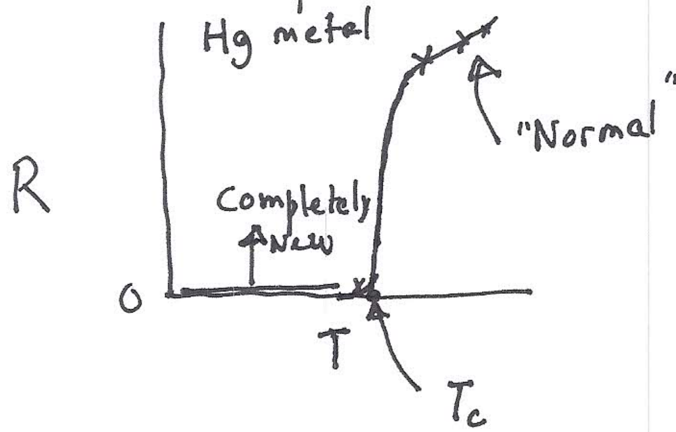
This year 2011 - 100^{th} anniversary.

ordinary conductors (Normal)

(metals)



Superconductors



$$R(T) = R(0) + AT^n$$

Impurity Scattering

electron-phonon electron-electron scattering

$T > T_c$ normal state

$T < T_c$ Supercond. state

~~Different~~

$R = 0 \Rightarrow \rho = 0 \Rightarrow \sigma = \infty$

$R : \Rightarrow \rho$ (Resistivity)

$= \frac{\rho L}{A}$

L, I

$\sigma = \frac{1}{\rho}$

conductivity

$$\boxed{\sigma = \frac{ne^2\tau}{m}}$$

$\sigma(T=0)$ is finite

$\Rightarrow \tau(T=0)$ "

Note: A "clean" normal metal can have

$\sigma = \infty$ at $T = 0$

Question. Is a superconductor (at $T < T_c$) $\equiv$ "clean" normal metal at T=0

NO

Some more experiments.

Three crucial

1) Meissner effect (Superconductor in the presence of an external magnetic field $\vec{B}_a$)

2) Heat capacity (electronic) for $T < T_c$; $C_{el} \neq \gamma T$

3) Isotope effect (T_c depends on the mass of atoms)

electronic phenomena

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4) Persistent current
5) Vortex state
6) Effect of magnetic impurities on T_c (T_c decreases)

Typical values of T_c :

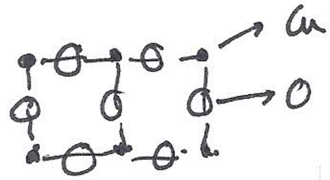
Pure metals	$T_c \lesssim 10$ K	Pb : 7.193 K
Intermetallics	$T_c \lesssim 30$ K	Hg : 4.153 K
		Nb_3Ge : 23.2 K

Some recent discoveries

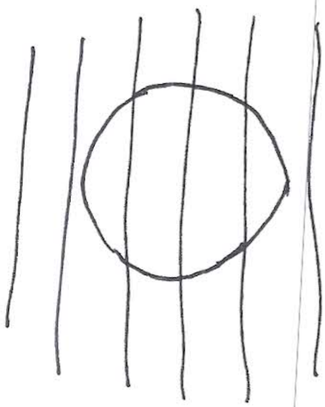
C_{60}	19.2 K
MgB_2	39.0 K
$YBa_2Cu_3O_{6.9}$	90.0 K
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$	138 K (Perhaps the highest T_c)

High-T_c superconductor

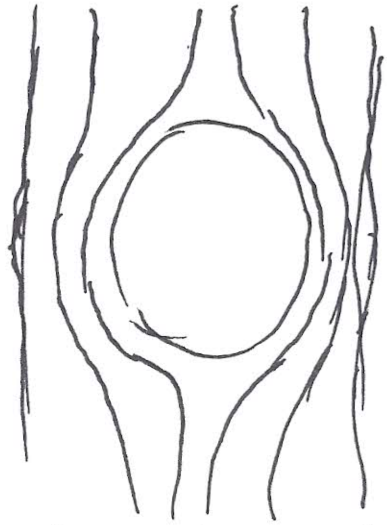
All have "CuO_2" 2d layers



Meissner Effect



$T > T_c$



$T < T_c$

Magnetic Flux get expelled from a superconductor (SC).

Inside SC

$B = B_a + 4\pi M$:

For $T < T_c$

$B = 0 \Rightarrow M = -\frac{1}{4\pi} B_a$

$= \chi B_a$

$\boxed{\chi = -\frac{1}{4\pi}}$ → Perfect diamagnet.

Imp. point

Ohms Law $\vec{E} = \rho \vec{J}$

Pass a current $\vec{J} \neq 0$,

For a supercond. $\rho = 0$ $\therefore$ $\vec{E} = 0$

Maxwell Eqn: $\vec{\nabla} \times \vec{E} + \frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0$

$\Rightarrow \frac{\partial \vec{B}}{\partial t} = 0$ or $\vec{B} = $ Constant

For a supercond. $\boxed{\vec{B} = 0}$

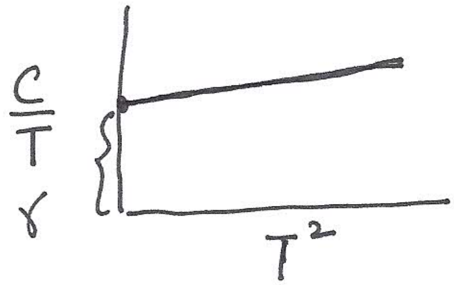
Question: What happens if we apply strong field to a superconductor?

It becomes normal:

Heat capacity and Energy gap

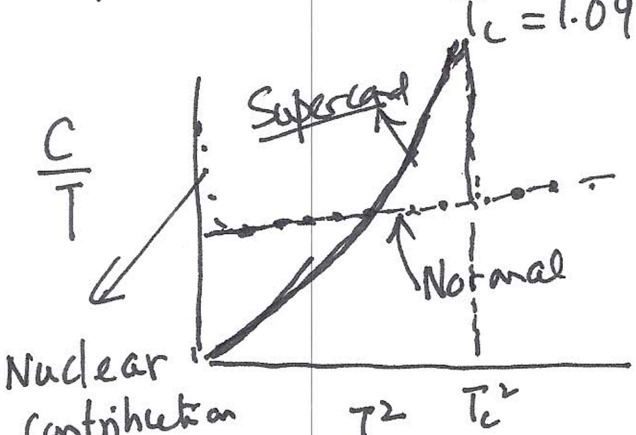
Recall: Normal metals $C = C_{el} + C_{latt} = \gamma T + AT^3$ (Debye law)

$$\frac{C}{T} = \gamma + AT^2$$



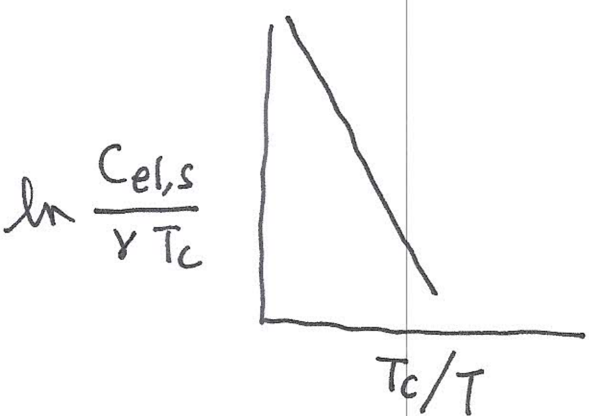
$T \ll \theta_D$

Expt. Ga metal



<u>Question:</u>
How do they measure C_{el} in the <u>normal state</u> for $T < T_c$?

Apply a small mag. field $B_a \sim 200\,G$
Kills the supercond. state



$$\Rightarrow \quad \frac{C_{el,s}}{\gamma T_c} = 7.46\, e^{-\Delta/k_B T}$$

$$\boxed{\Delta = 1.39\, k_B T_c}$$

There is an energy gap in the electronic excitation spectrum.

<u>Physics of this gap formation</u> (Electron-phonon interaction $\Rightarrow$ Cooper Pairs)

<u>Isotope Effect</u>

$$T_c = \frac{\text{Const}}{M^{\alpha}}$$

$\alpha \simeq 0.5$ (<u>some simple metals</u>)

$\simeq 0.$ (other metals, Alloys).