

SUMMARY - ELECTRONIC SPECIFIC HEAT

$$C_V = \gamma \cdot T$$

γ = SOMMERFELD CONSTANT

$$\gamma = \frac{\pi^2}{3} D(\epsilon_F) k_B^2$$

$$= \frac{\pi^2}{2} N \cdot k_B \frac{1}{T_F}$$

DIFFERENT
FORMULATIONS
OF THE SAME
RESULT

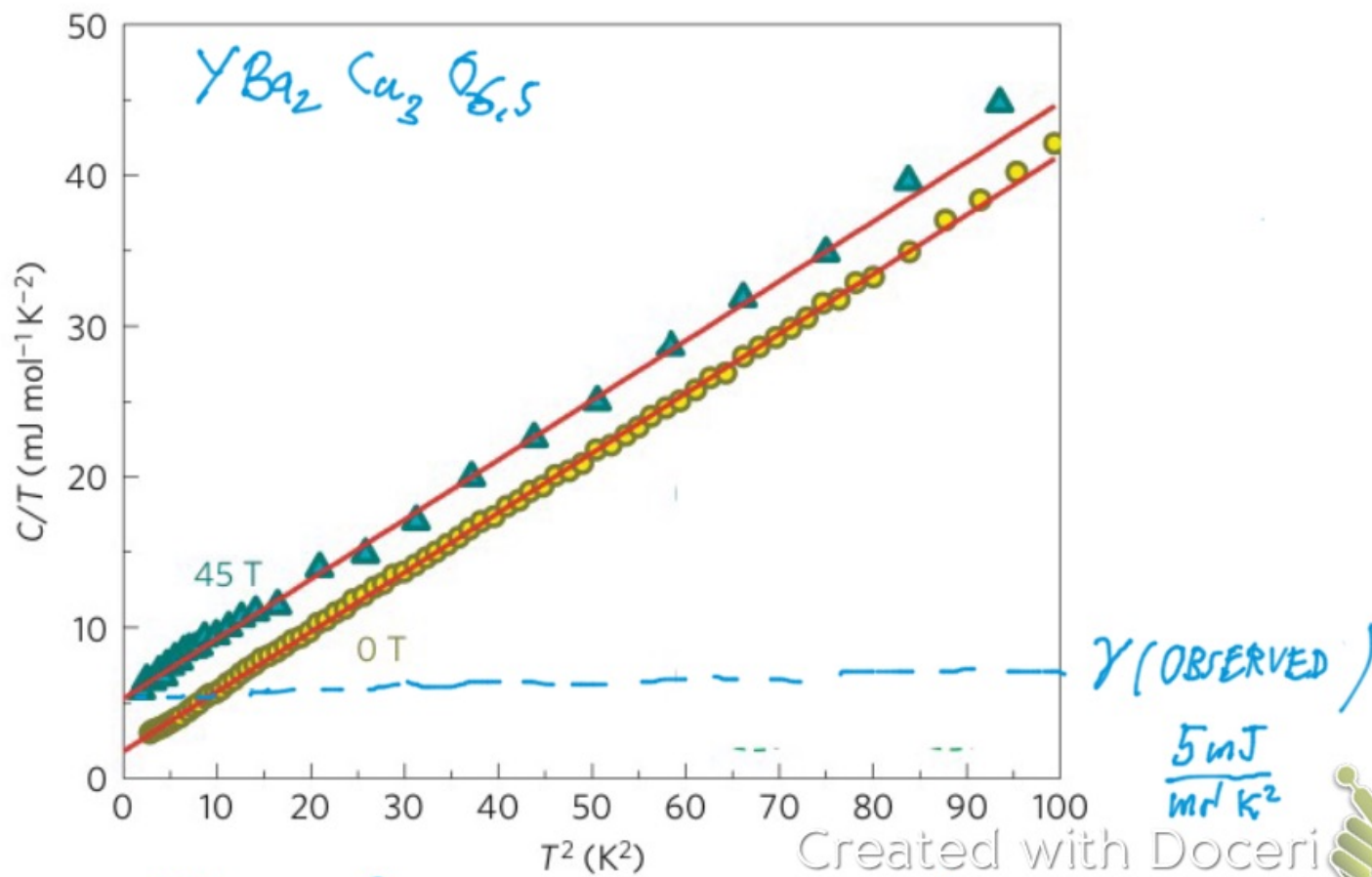
EXERCISE: Show that $\gamma \propto m$ where
 $m = \text{electron mass}$

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ELECTRONIC MASS

$$\frac{\gamma(\text{OBSERVED})}{\gamma_{\text{free}}} = \frac{m_{\text{OBSERVED}}}{m_{\text{free}}}$$

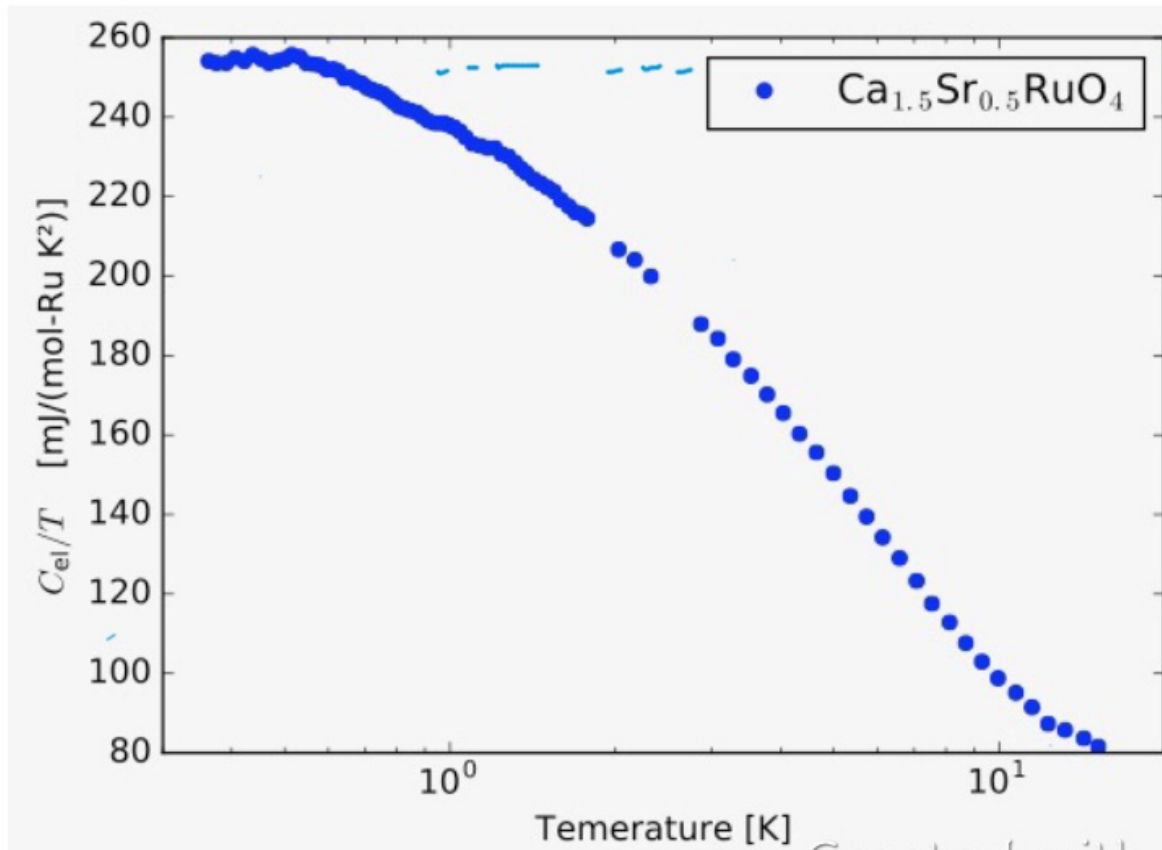


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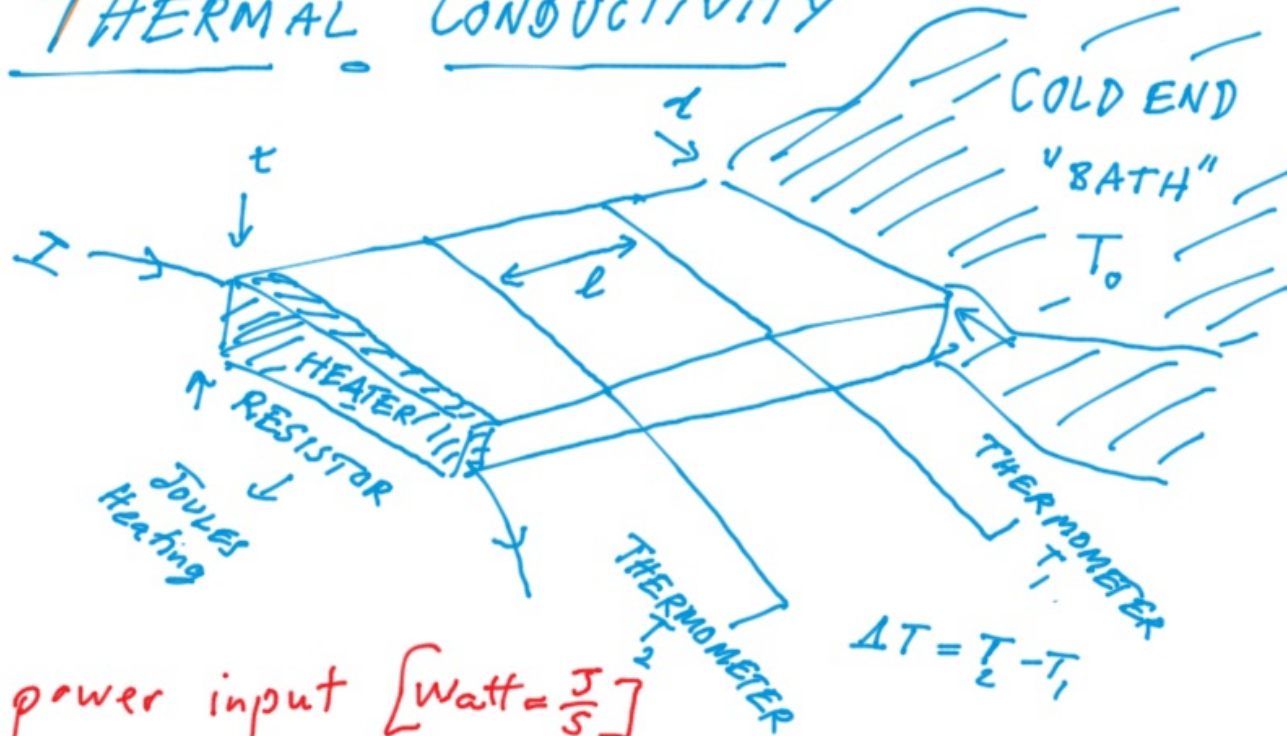
HEAVY-FERMIONS:



--- γ (OBSERVED)
 $250 \frac{\text{mJ}}{\text{mol K}^2}$

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THERMAL CONDUCTIVITY



$P = \text{power input [Watt} = \frac{J}{s}]$

$A = \text{cross section} = t \cdot d$

$$k = \text{thermal conductivity} \equiv \frac{P/A}{\Delta T/l} = \frac{l}{A} \cdot \frac{P}{\Delta T}$$

$$k_{el} \propto C \propto T$$

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THERMOPOWER / SEEBECK EFFECT

The diagram illustrates the Seebeck effect setup. A rectangular block is shown with a 'HOT HEATER RESISTOR' on the left and a 'COLD' end on the right. The hot end is connected to a 'HEATER' and a 'RESISTOR' through which current I flows. The hot end is labeled 'HOT' and the cold end is labeled 'COLD'. The cold end is immersed in a 'COLD END "/>

Two graphs are shown on the left:

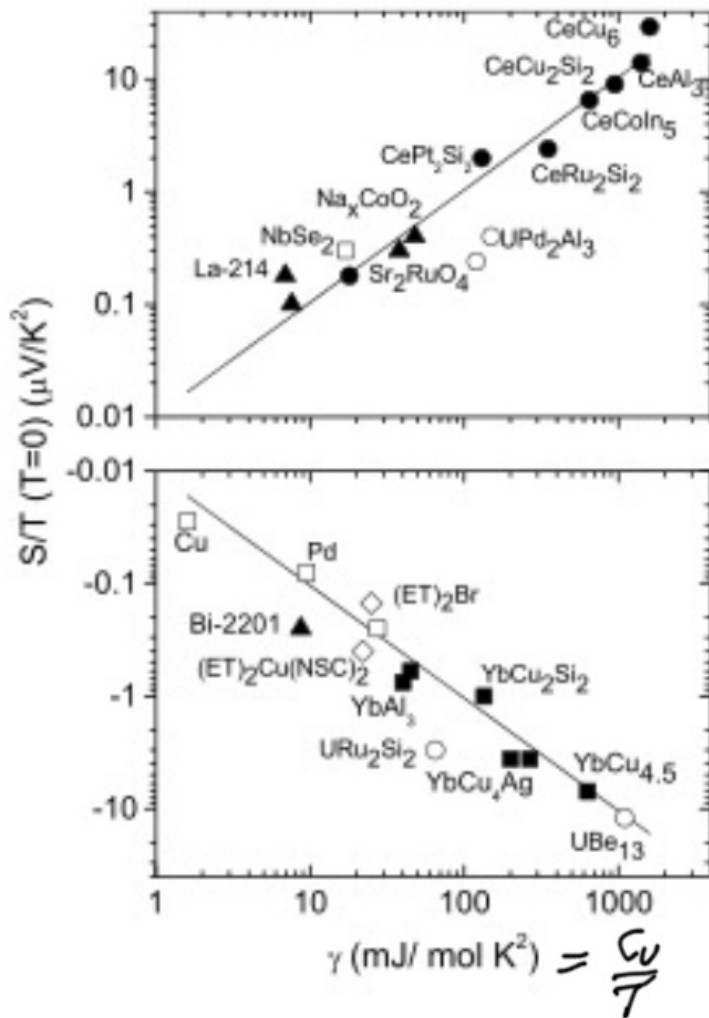
- The top graph plots $f(\epsilon)$ vs ϵ . It shows a red curve representing the Fermi-Dirac distribution and a green step function representing the density of states.
- The bottom graph plots $f(\epsilon)$ vs ϵ . It shows a red curve that is constant up to the Fermi energy ϵ_F and then drops to zero.

Key labels and equations in the diagram include:

- ΔV (voltage difference)
- $\Delta T = T_2 - T_1$ (temperature difference)
- Thermometer labels T_1 and T_2
- Equation for Seebeck coefficient:
$$S \equiv \frac{\Delta V}{e} / \frac{\Delta T}{e} = \frac{\Delta V}{\Delta T}$$
- Equation for Seebeck coefficient:
$$S = -\frac{\pi^2 k_B^2 T}{6 e T_F}$$

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COMPARE: SPECIFIC HEAT & THERMOPOWER



$$S = \frac{\pi^2}{2} \frac{k_B}{e} \frac{T}{T_F}$$

$$C_V = \frac{\pi^2}{2} N \cdot k_B \frac{T}{T_F}$$

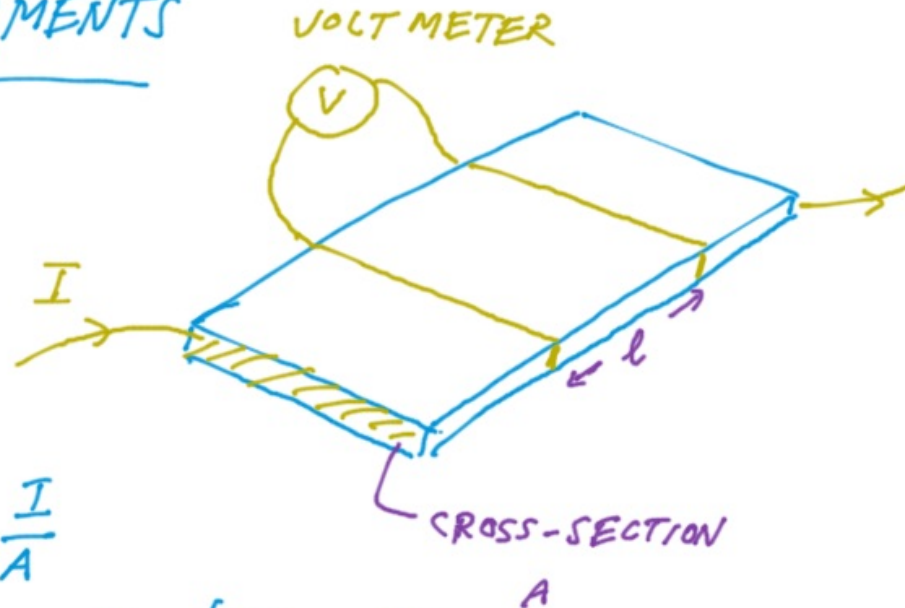
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Resistivity EXPERIMENTS

Ohm's Law : $V = R \cdot I$

$R =$ RESISTANCE



CURRENT DENSITY : $j = \frac{I}{A}$

VOLTAGE BETWEEN 2 POINTS : $V = \int E dx = E \cdot l$
ELECTRICAL FIELD

Ohm's Law Reformulated :

$$El = R \cdot Aj \Rightarrow E = \frac{l}{A} \cdot Rj = \rho \cdot j$$

or

$$j = \sigma E$$

where $\rho = \frac{l}{A} R =$ resistivity
 $\sigma = \frac{1}{\rho} =$ conductivity



DRUDE CONDUCTIVITY

$$m \frac{dv}{dt} + \frac{mv}{\tau} = F = -eE$$

$$E \propto e^{i\omega t}$$

$$v \propto e^{i\omega t}$$

$$(i\omega + \frac{1}{\tau})mv = -eE \Rightarrow v = \frac{-eE}{(i\omega + \frac{1}{\tau})m} \stackrel{\text{DC}}{\omega \rightarrow 0} = -\frac{eE\tau}{m}$$

$$j = -nev = \frac{ne^2\tau}{m} \cdot E$$

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

$$\rho = \frac{m}{ne^2\tau} = \frac{1}{ne\mu}$$

where $\mu = \frac{e\tau}{m} = \text{electron mobility}$

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LANDAU FERMION LIQUID: electron-electron scattering

Related to impurity scattering

scattering

$$\rho = \rho_0 + A \cdot T^2$$

ρ_0 = Residual resistivity

RESIDUAL-RESISTIVITY RATIO

$$RRR = \frac{\rho(300K)}{\rho(0K)}$$

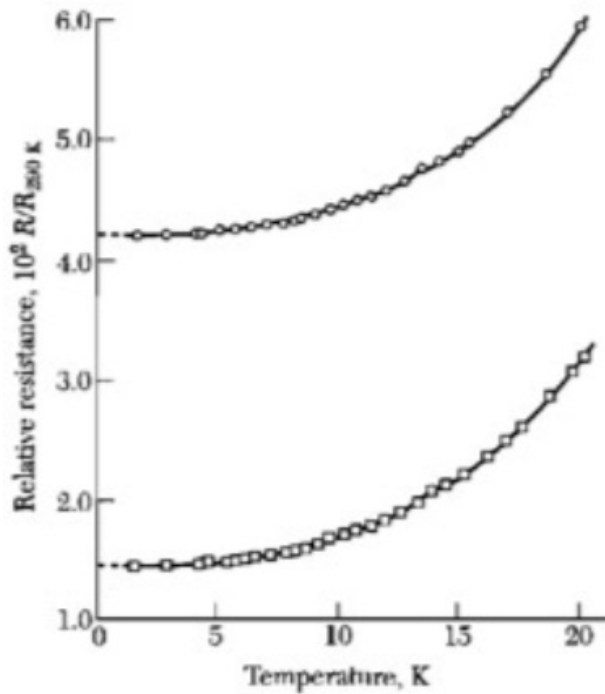
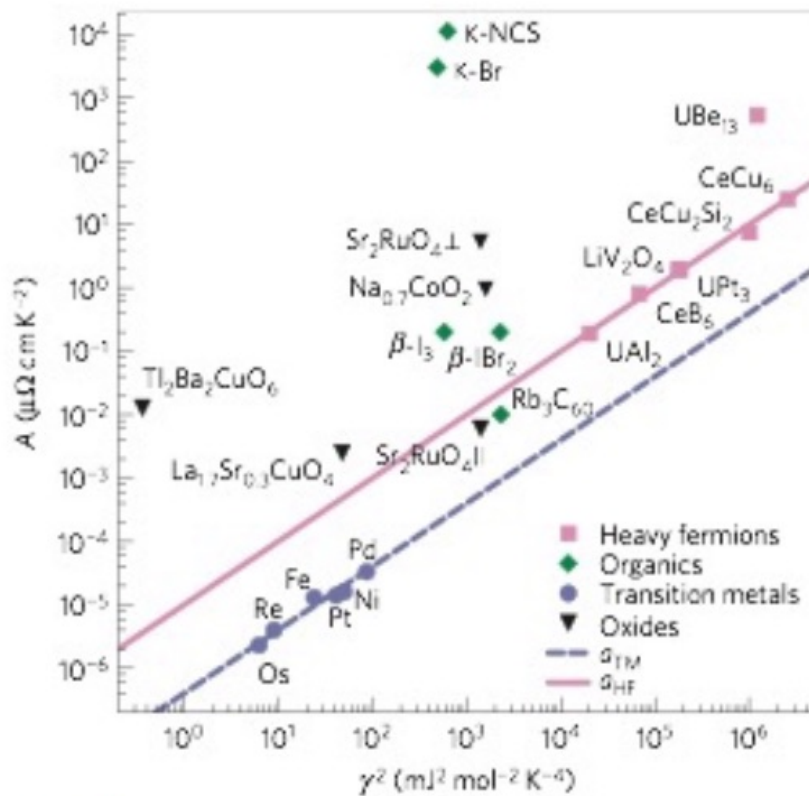


Figure 12 Resistance of potassium below 20 K, as measured on two specimens by D. MacDonald and K. Mendelssohn. The different intercepts at 0 K are attributed to different concentrations of impurities and static imperfections in the two specimens.

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KADOWAKI - Woods Relation: HUMAN RATIONALIZATION



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WIEDERMANN - FRANZ RELATION:

$$\sigma = \frac{n e^2 \tau}{m}$$

$$\kappa_{el} = \frac{1}{3} C \cdot v \cdot l = \frac{\pi^2 n k_B^2 T \tau}{3m} \quad (\text{See KITTEL})$$

$$\Downarrow \frac{\kappa_{el}}{\sigma} = \frac{\pi^2}{3} \left(\frac{k_B}{e} \right)^2 \cdot T$$

NOT TO FORGET
($T \rightarrow 0$ K limit)

LORENZ NUMBER

$$L \equiv \frac{\kappa_{el}}{\sigma \cdot T} = \frac{\pi^2}{3} \left(\frac{k_B}{e} \right)^2 = 2.45 \cdot 10^{-8} \text{ Watt} \cdot \Omega / \text{K}^2$$

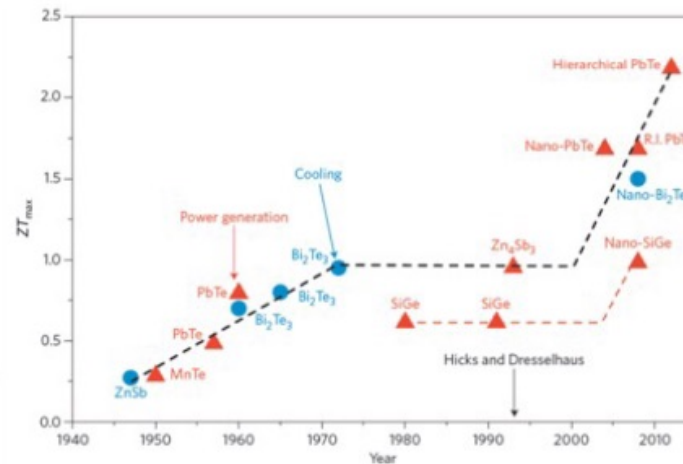
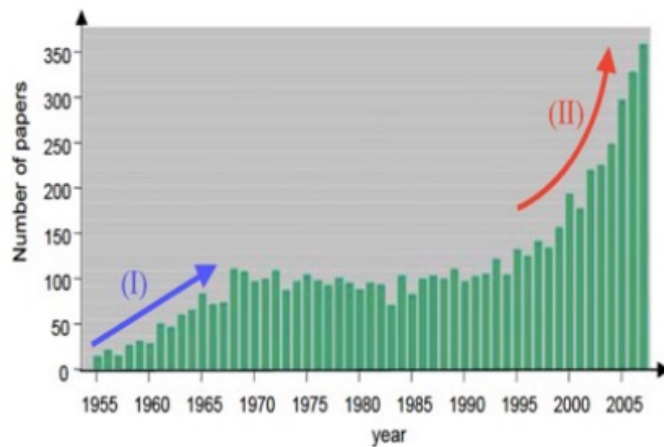
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THERMO-ELECTRICITY: FIGUR-OF-MERIT

$$ZT = \frac{\sigma S^2 \cdot T}{\kappa} \quad (\text{HUMAN CONSTRUCTION})$$

$$\kappa = \kappa_{\text{phonons}} + \kappa_{\text{electrons}}$$



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HALL EFFECT:

$$R_{xx} = \frac{V_x}{I_x} \quad ; \quad \rho_{xx} = \frac{E_x}{j_x}$$

$$\rho_{xy} = \frac{E_y}{j_x} = \frac{V_y/w}{I_x/wt} = \frac{V_y \cdot t}{I_x}$$

$$R_{xy} = \frac{V_y}{I_x} = \rho_{xy} \cdot \frac{1}{t}$$

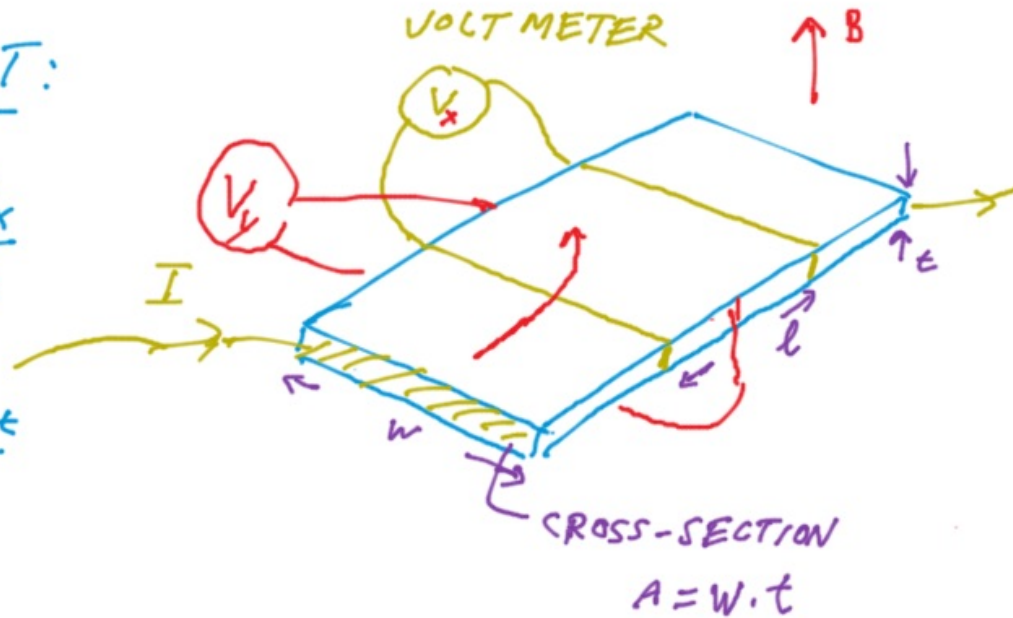
$$(0) \quad F = -e (\vec{E} + \vec{v}_d \times \vec{B}) \quad \text{FORCE}$$

$$(1) \quad E_y = v_x \cdot B_z$$

$$(2) \quad j_x = -en v_x$$

$$(3) \quad V_y = E_y \cdot w = v_x \cdot B_z \cdot w = \frac{-j_x}{ne} B_z \cdot w = \frac{-I_x}{w \cdot t} \cdot \frac{B_z}{en} \cdot w = \frac{-I_x}{t} \frac{B_z}{en}$$

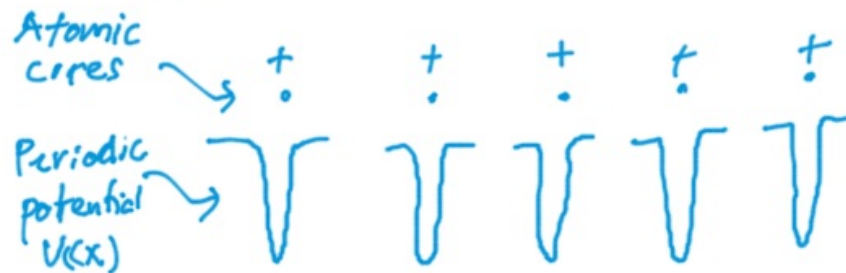
$$\rho_{xy} = \frac{-B}{en} \Rightarrow R_H \equiv \frac{\rho_{xy}}{B} = \frac{-1}{en} = \text{HALL COEFFICIENT}$$



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BAND STRUCTURE - BACKGROUND:



Schrödinger Equation

$$\left\{ \frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + V(x) \right\} \psi(x) = E \psi(x)$$

What happens to $\psi(x)$ and E when $V(x) \neq 0$.

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