FUNDAMENTALS OF NANOELECTRONICS

Basic Concepts

1. The New Perspective
2. Energy Band Model
3. What and Where is the Voltage?

Heat & Electricity: Second Law & Information

4.1. Introduction

4.2. Seebeck Coefficient

4.3. Heat Current

4.4. One-level Device

4.5. Second Law

4.6. Entropy

4.7. Law of Equilibrium

4.8. Shannon Entropy

4.9. Fuel Value of Information

4.10. Summing up ..

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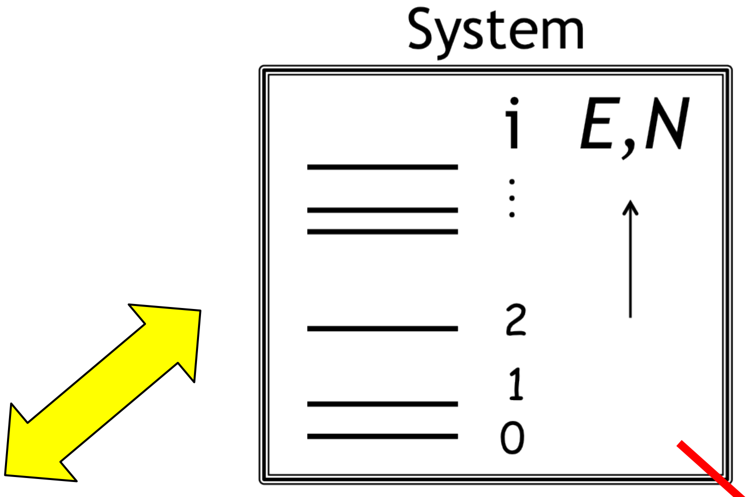
4.7a Law of equilibrium



$$p_i = \frac{1}{Z} e^{-(E_i - \mu N_i)/kT}$$

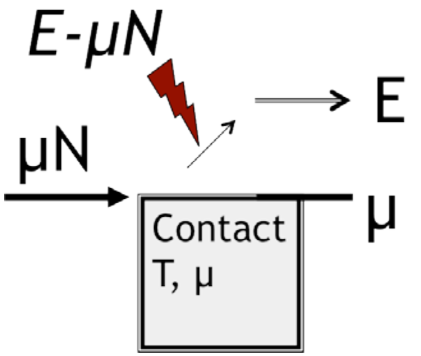
$$E = E_1 - E_2$$

$$N = N_1 - N_2$$

$$(E_2, N_2) \xrightarrow{P(E,N)} (E_1, N_1)$$

$$(E_2, N_2) \xleftarrow[P_r(E,N)]{} (E_1, N_1)$$

$$p_1 \, P_r(E,N) = p_2 \, P(E,N)$$

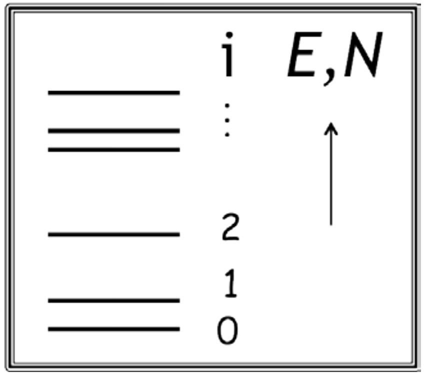


$$\frac{P(E,N)}{P_r(E,N)} = \exp\left(-\frac{E - \mu N}{kT}\right)$$

4.7b Law of equilibrium

$$p_i = \frac{1}{Z} e^{-(E_i - \mu N_i)/kT}$$

System



$$E = E_1 - E_2$$

$$N = N_1 - N_2$$

$$(E_2, N_2) \xrightarrow{P(E,N)} (E_1, N_1)$$

$$(E_2, N_2) \xleftarrow[P_r(E,N)]{} (E_1, N_1)$$

$$= \frac{\exp\left(-\frac{E_1 - \mu N_1}{kT}\right)}{\exp\left(-\frac{E_2 - \mu N_2}{kT}\right)}$$

$$\frac{p_1}{p_2} = \frac{P(E,N)}{P_r(E,N)} = \exp\left(-\frac{E - \mu N}{kT}\right)$$

$$p_1 \, P_r(E,N) = p_2 \, P(E,N)$$

Contact

$$\frac{P(E,N)}{P_r(E,N)} = \exp\left(-\frac{E - \mu N}{kT}\right)$$

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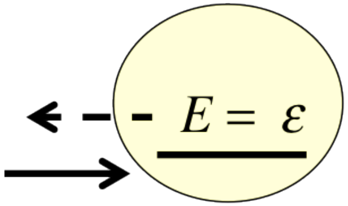
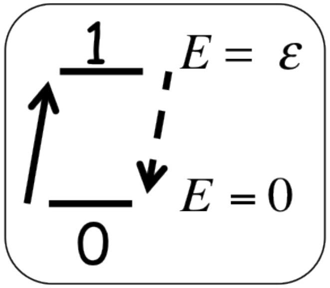
4.7c Law of equilibrium

One-electron picture



"Fock space"



$$\frac{E_i - \mu N_i}{kT}$$

$$x$$

$$0$$

$$p_i = \frac{1}{Z} e^{-(E_i - \mu N_i)/kT}$$

$$x = \frac{\varepsilon - \mu}{kT}$$

$$p_0 = \frac{1}{Z} = \frac{1}{1+e^{-x}}$$

$$p_1 = \frac{e^{-x}}{Z} = \frac{e^{-x}}{1+e^{-x}} = \frac{1}{1+e^{x}}$$

$$\langle N \rangle = 0 \times p_0 + 1 \times p_1$$

Fermi function $= \dfrac{1}{1+e^{x}}$

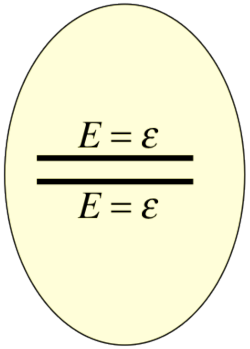
$$\frac{1+e^{-x}}{Z} = 1 \rightarrow Z = 1 + e^{-x}$$

$$p_0 + p_1 = 1$$

4.7d Law of equilibrium

$$p_i = \frac{1}{Z} e^{-(E_i - \mu N_i)/kT}$$

2 one-electron levels	Fock space states	E_i	N_i	$\frac{E_i - \mu N_i}{kT}$
	11	$2\varepsilon + U_0$	2	$2x + y$
	01, 10	ε	1	x
	00	0	0	0



$$p_{00} = \frac{1}{Z}, \quad p_{01} = p_{10} = \frac{e^{-x}}{Z}, \quad p_{11} = \frac{e^{-2x} e^{-y}}{Z}$$

$$y = 0 \rightarrow (1-f)^2, \quad f(1-f), \quad f^2$$

$$x \equiv \frac{\varepsilon - \mu}{kT}$$

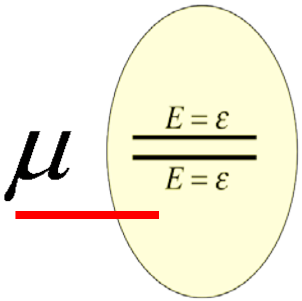
$$y \equiv \frac{U_0}{kT}$$

4.7e Law of equilibrium

$$p_i = \frac{1}{Z} e^{-(E_i - \mu N_i)/kT}$$

$$x \equiv \frac{\varepsilon - \mu}{kT}, \quad y \equiv \frac{U_0}{kT}$$

2 one-electron levels



Fock space states

$$\frac{E_i - \mu N_i}{kT}$$

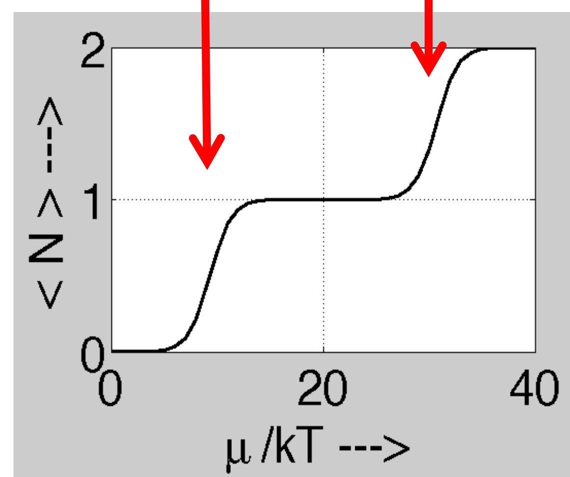
11 — → $2x + y$

01 — — 10 → x

00 → 0

$x = 0$ → $\mu = \varepsilon$

$x = 2x + y$ → $\mu = \varepsilon + U_0$



1 **0**

$$p_1 = \frac{e^{-100}}{Z}, \quad p_2 = \frac{e^{-200}}{Z}$$

$$Z = e^{-100} + e^{-200}$$

$kT \rightarrow 0$

$p_i = 1,$ *for state with* $\min imum\ E_i - \mu N_i$

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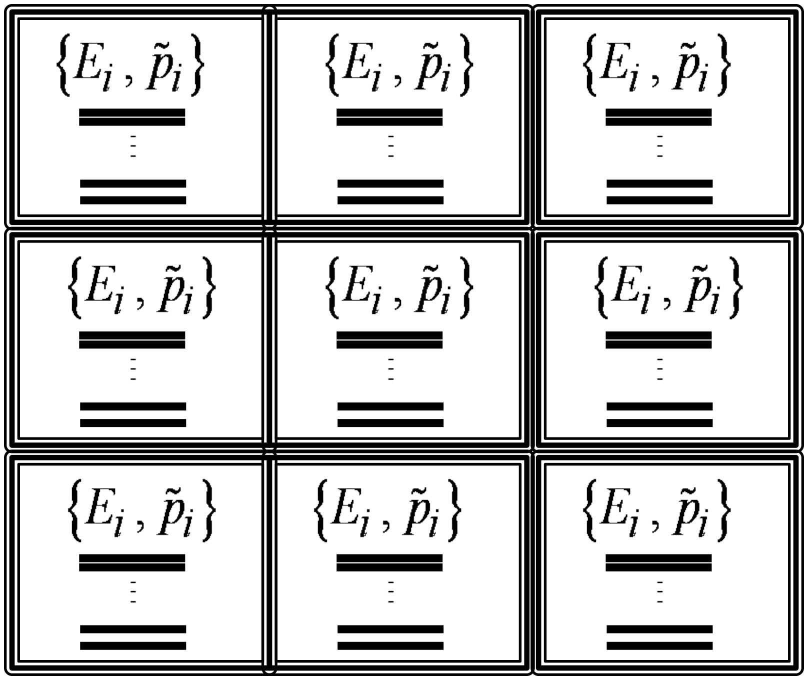
$$S = k \, \ell n W$$

Coming up next ..

N identical systems



$$S = -N k \sum_i \tilde{p}_i \, \ell n \, \tilde{p}_i$$