

I. Classical Ideal Gases

$$A. F = +N\tau \left[\ln\left(\frac{n}{n_a}\right) - 1 \right] \quad (n < n_a)$$

$$\mu = \tau \ln\left(\frac{n}{n_a}\right) \quad (< 0)$$

$$P = n\tau \quad U = \frac{3}{2}N\tau \Rightarrow PV = \frac{2}{3}U, \sigma = N \left[\ln \frac{n_a}{n} + \frac{5}{2} \right] \left(= \frac{\partial F}{\partial \tau} \right)$$

B. Internal degrees of freedom:

$$n_a \rightarrow n_a Z_{\text{int}} \quad (\text{e.g. } Z_{\text{int}} = (2S+1) Z_{\text{rot}} Z_{\text{ vib}})$$

C. Processes in ideal gases (reversible)

(isothermal expansion) $\quad (\tau = \text{const.} \propto PV)$

expansion at constant entropy ($n_a V = \text{const.}$)

II. Quantum Ideal Gases - Fermi and Bose gases

A. Fermi Gas

$$1. \quad E_F = \frac{\hbar^2}{2m} \left(\frac{\pi}{L} n_F \right)^2 \quad N = 2 \cdot \frac{1}{8} \cdot \frac{4}{3} \pi n_F^3 = \frac{\pi n_F^3}{3}$$

$$2. \quad \text{Pressure } U_0 = \frac{3}{5} N E_F \Rightarrow P = -\frac{\partial U_0}{\partial V} = \frac{2}{5} \frac{U_0}{V} \quad (\Gamma = 0)$$

$$C_V \approx \frac{k^2}{2} N \frac{\tau}{\epsilon_F} \quad (\epsilon_F = E_F) \quad \tau \ll \tau_F$$

B. Density of states

$$\Theta_F(E) = \frac{3}{2} \frac{N}{E_F} \left(\frac{E}{E_F} \right)^{1/2} \quad [\text{from } E = \frac{\hbar^2}{2m} \left(\frac{2\pi^2 N(E)}{V} \right)^{2/3}, dN(E) = \frac{dN}{dE}]$$

B. Bose Gas

$$1. \quad \Theta_B(E) = \frac{1}{2} \Theta_F(E) \quad N(E) = 1 \cdot \frac{1}{8} \cdot \frac{4}{3} \pi n_E^3 \quad n_E = \left(\frac{6N(E)}{\pi} \right)^{1/3}$$

$$\epsilon = \frac{\hbar^2}{2m} \left(\frac{\pi}{L} \right)^2 n_E^2 = \frac{\hbar^2}{2m} \left(\frac{6N(E)}{V} \right)^{2/3}$$

$$2. \quad \begin{cases} \mu \leq 0 \text{ all } \tau \\ \mu \rightarrow 0 \text{ at } \tau = \tau_E > 0 \end{cases} \Leftarrow \text{B-E condens.}$$

$$E = \frac{\hbar^2}{2m} \left(\frac{\pi}{L} \right)^2 n^2 \quad N(E) = g_s \frac{1}{8} \frac{4}{3} \pi n_E^3$$

III. Non-degenerate Semiconductors (ideal gas of quasiparticles)

$$A. \quad n_e = n_c e^{-(E_c - \mu)/kT} \quad n_c \equiv 2 \left(\frac{m_e^* \tau}{2\pi\hbar^2} \right)^{3/2}$$

$$n_h = n_v e^{-(\mu - E_v)/kT} \quad n_v \equiv 2 \left(\frac{m_h^* \tau}{2\pi\hbar^2} \right)^{3/2}$$

$$n_e n_h = n_i^2 = n_e n_v e^{-E_g/kT}$$

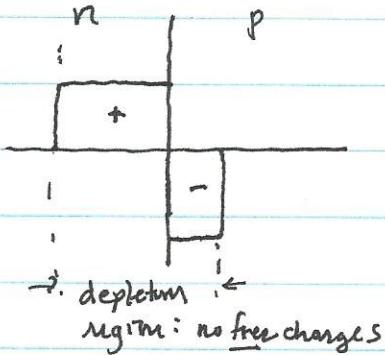
$$n_e - n_h = \Delta n = n_d^+ - n_a^-$$

$$N(E) = g_s \frac{1}{4} (\pi n_E^2)$$

$$B. \quad n\text{-type: } n_e = n_d \quad n_h \approx \frac{n_i}{n_d} n_i \ll n_i$$

$$p\text{-type } n_h = n_a \quad n_e \approx \frac{n_i}{n_a} \quad n_i \ll n_i$$

C. Built-in potential \Rightarrow depletion region



IV Heat, Work

$$A. \tilde{Q}_{abs} = T d\sigma \quad \tilde{W}_{on} = -pdV \quad dU = \tilde{Q}_{abs} + \tilde{W}_{on}$$

heat abs. by system work done on system

$$\text{cycle: } \oint dU = 0 = \oint \tilde{Q}_{abs} + \oint \tilde{W}_{on}$$

B. Carnot cycle : \uparrow

(PV diagrams)
for cycles

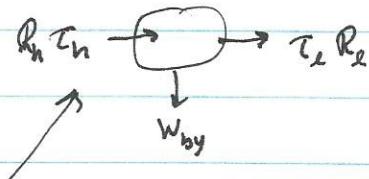
1. const T exp.

2. const σ exp.

3. const T comp.

4. const σ comp.

$$5. \left(\frac{W_{by}}{Q_{in}} \right) = \frac{T_h - T_c}{T_h} \equiv \eta_C \quad (\text{reversible})$$



C. Refrigerator and heat pump

$$1. \left(\frac{Q_{in}}{W_{on}} \right) = \frac{T_c}{T_h - T_c} \equiv \gamma_C \quad (\text{reversible}) \quad R_h T_c \xrightarrow{\text{(invers)}} R_c T_h \quad (\text{irreversible})$$

2. \uparrow refriger. \rightarrow heater : reverse

D. Ideal Gas Cycles

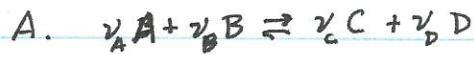
E. Thermodynamic potentials

$$1. F = \text{isothermal work} = U - T\sigma \quad (\Delta U)_T = (dF)_T + (d(T\sigma))_T$$

$$2. H = U + pV \quad (dH)_p = \tilde{W}' + \tilde{Q}_p \quad \text{enthalpy}$$

$$3. G = F + pV = \mu_j N_j \quad \tilde{W}' = (dG)_{T,p} \quad (\text{e.g. } \mu_d N_d)$$

IV Chemical reaction equilibrium



$$\Rightarrow \nu_A \mu_A + \nu_B \mu_B - \nu_C \mu_C - \nu_D \mu_D = 0 \quad \left(\sum_j p_j \mu_j = 0 \right)$$

B. For ideal gases, A. gives law of mass action

C. A. applies even outside ideal gas limit.