

Free Energy & Chemical Thermodynamics

5.1) Free energy

• Enthalpy $H = U + PV$

• Helmholtz free energy $F = U - TS$

especially
useful at
const T, V

• Gibbs free energy $G = U + PV - TS$

• F : the energy that must be provided as work (if you are creating the system out of nothing)

the energy that comes out as work (if you annihilate the system)

• G : The work you need to do to create a system in environment (T, P, const)

The work you can recover when you destroy it.

$U, H, F \& G$: Thermodynamic potentials

Thermodynamic Identities

- $H = U + PV$

$$dH = dU + PdV + VdP$$

$$= Tds - PdV + \mu dN + PdV + VdP$$

$$dH = Tds + \mu dN + VdP$$

- $F = U - TS$

$$dF = dU - Tds + SdT$$

$$= \cancel{Tds} - PdV + \mu dN - \cancel{Tds} + SdT$$

$$dF = -PdV + \mu dN + SdT$$

- $G = U + PV - TS$

$$dG = dU + PdV + VdP - Tds - SdT$$

$$= Tds - PdV + \mu dN + PdV + VdP - Tds - SdT$$

$$dG = \mu dN + VdP - SdT$$

At const P, N

$$dG = -SdT \Rightarrow S = -\left(\frac{\partial G}{\partial T}\right)_{P,N}$$

Pb 5.12) Maxwell Relations, Hold N constant

$$dU = TdS - PdV + \mu dN$$

$\left(\frac{\partial U}{\partial S}\right)_{V,N}$ $\left(-\frac{\partial U}{\partial V}\right)_{N,S}$ $\left(\frac{\partial U}{\partial N}\right)_{V,S}$

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy + \frac{\partial f}{\partial z} dz$$

إذا أخذت التغيير الترتيب عشوائي $\frac{\partial}{\partial y \partial x} = \frac{\partial}{\partial x \partial y}$

$$\frac{\partial}{\partial V} \left(\frac{\partial U}{\partial S} \right)_{N,V} = \frac{\partial}{\partial S} \left(\frac{\partial U}{\partial V} \right)_{N,S}$$

$$\frac{\partial (T)}{\partial V} \Big|_{S,N} = \frac{\partial (-P)}{\partial S} \Big|_{V,N}$$

$$\left. \frac{\partial T}{\partial V} \right|_{S,N} = - \left. \frac{\partial P}{\partial S} \right|_{V,N}$$

Maxwell Relation:

$$dH = T ds + v dP \quad , \quad \text{holding } N \text{ const.}$$

$$\frac{\partial}{\partial P} \left(\frac{\partial H}{\partial S} \right) = \frac{\partial}{\partial S} \left(\frac{\partial H}{\partial P} \right)$$

$\frac{\partial T}{\partial P} = \frac{\partial v}{\partial S}$

في ثقلات متساوية

في ثقلات متساوية

في ثقلات المتساوية

مدالة المياه

$$dG = \mu dN - S dT + v dP$$

في ثقلات متساوية
في ثقلات متساوية

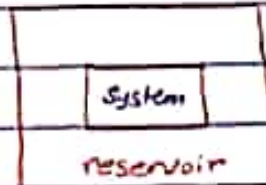
$$\frac{\partial}{\partial T} \left(\frac{\partial G}{\partial P} \right) = \frac{\partial}{\partial P} \left(\frac{\partial G}{\partial T} \right)$$

$$\frac{\partial v}{\partial T} = - \frac{\partial S}{\partial P}$$

5.2 Free energy as a force toward equilibrium

دما، تفرقی معنی جزیلاتی
 ام ایسی حکیمانہ قول انہ S داتا مستویہ
 علا F+G لازم ہ

نظام الی اجنا جینا مدرسه فکون وین اثرات
 بینہ ویں ال reservoir



Environment has constant T

$$S_{tot} = S + S_R$$

$S_R = \text{reservoir Entropy}$

$$dS_{tot} = dS + dS_R$$

$$dS = \frac{1}{T} dU + \frac{P}{T} dV - \frac{\mu}{T} dN$$

used for reservoir here

دما نشوف بالقر التزان ال کبر

1st case: Constant V, N for reservoir

$$dS_{tot} = dS + \frac{1}{T_R} dU_R$$

$$T_R = T$$

$dU_R = -dU$ (بالواحد حتم التوافق
بكمب)

$$dS_{tot} = dS + \frac{1}{T} (-dU)$$

عادل على F
متوزل عتبات
ب.س.س
Equilibrium

$$dS_{tot} = -\frac{1}{T} (dU - T dS)$$

$$dS_{tot} = -\frac{1}{T} (-dF)$$

for system

- The ^{whl} entropy of the universe increases, if F of system decreases (the system try to minimize F)

لا بدى اعرف الكمية spontaneous او لا ط اكون عيبه الحجم
F (طاقة)

const V, T

Case 2 Constant T, P, N
Variable V

System
variables
Gibbs
energy

$$dS_{\text{tot}} = dS_{\text{sys}} + dS_R$$

$$\frac{1}{T_R} dU_R + \frac{P_R}{T_R} dV_R$$

$dS_{\text{tot}} \uparrow$

$$dS_{\text{tot}} = dS_{\text{sys}} - \frac{dU_{\text{sys}}}{T_{\text{sys}}} - \frac{P_{\text{sys}}}{T_{\text{sys}}} dV$$

$$dS_{\text{tot}} = dS - \frac{dU}{T} - \frac{P}{T} dV$$

limit T
limit P
 $-V = V_R$

$$dS_{\text{tot}} = dS_{\text{tot}} = -\frac{1}{T} dG_{\text{sys}}$$

Gibbs free energy
tends to decrease
at const T, P, N

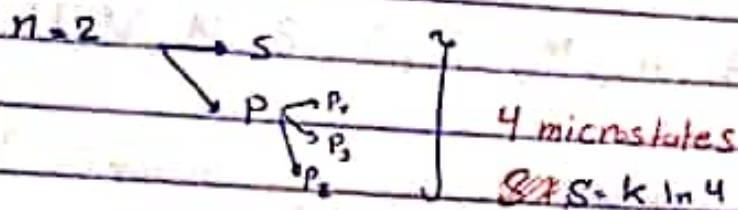
Summary)

At const N .

- Constant U, V : $S \uparrow$
- Constant T, V : $F \downarrow$
- Constant T, P : $G \downarrow$

Q5.20 Hydrogen atom

$n=2$, $n=1$
 \downarrow \downarrow
 10.2 eV 0 eV



$n=1 \rightarrow s$ } $S = k \ln 1 = 0$

مناخات سرعة الفوتون التي يمر عندها إنتقال الإلكترونات من $n=2$ إلى $n=1$ ^{مطابق}
 الكميات

$F = U - TS$

$\Delta F = \Delta U - T \Delta S$

$0 = 10.2 - T(k \ln 4)$

$T = \frac{10.2}{k \ln 4} \approx 85.000 \text{ K}^\circ$

في تفاعل كيمياء
 ديناميكية من جانب
 التوازن بتزويد
 الاحتمالية
 عند انتقال من
 احتمال من
 احتمال

Extensive & Intensive Quantities

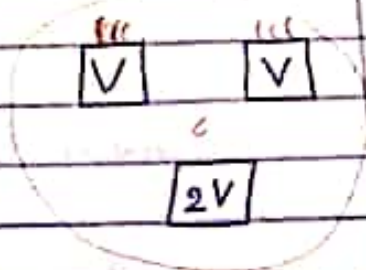
القيم التي تعرفنا على الحد الآن

$U, V, N, S, T, P, \mu, H, F, G$

هل هي مكثفة أو ممتدة؟ Thermal Quantities
 Extensive
 Intensive

Extensive Quantities

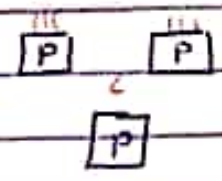
V, N, S, U, Mass



مما صنفه
 V كل واحد
 لو جاب كان واحد
 الحجم جيبير $2V$

Intensive Quantities

$T, P, \mu, \text{density}$



من ايها علاقة
 بالتركيز
 ما يتغير

في عمليات حسابية

Rules

[1] $T \times E = E$
 $pV = nT$

[4] $E + E = E$

[2] $E \times E$: will not happen in thermal physics

[5] $I + E$: not Allowed

[3] $T + T = T$

[6] $\frac{E}{E} = I$

[7] $\frac{E}{I} = E$

$$G = U - TS + PV$$

$$E - TE + TE$$

$$= E - E + E \Rightarrow \text{Extensive}$$

5.21) Heat Capacity = $\frac{\Delta Q}{\Delta T} = \frac{E}{T} = E$

Specific heat = $\frac{1}{m} \frac{\Delta Q}{\Delta T} = \frac{E}{E} = T$

Gibbs Free Energy & Chemical Potential

System لا
نظام

Start with

$$\mu = \left(\frac{\partial G}{\partial N} \right)_{T,P}$$

$$dG = \mu dN$$

إذا كانت درجة الحرارة والضغط

يكون

ال
Chemical Potential

التغير في Gibbs

• Holding T, P , if we add one particle to a system, G changes by μ .

• If we add N particles, G changes by $N\mu$.

$$G = N\mu$$

غرفا كمية نظام واحد في System ونفس الظروف في مادي

for more than one type of particles

$$G = N_1 \mu_1 + N_2 \mu_2 + N_3 \mu_3$$

$$= \sum_i N_i \mu_i$$

Application of $G = N\mu$ for an Ideal Gas at $T, N = \text{const}$ & P is varied

$$G = N\mu \quad ; \quad V = \left(\frac{\partial G}{\partial P} \right)_{T, N}$$

Chemical Identity for Ideal Gas

$$\frac{\partial \mu}{\partial P} = \frac{\partial}{\partial P} \left(\frac{G}{N} \right) = \frac{1}{N} \left(\frac{\partial G}{\partial P} \right)_{T, N}$$

$$\frac{\partial \mu}{\partial P} = \frac{1}{N} V \quad ; \quad PV = NkT$$

$$\frac{V}{N} = \frac{kT}{P}$$

$$\frac{\partial \mu}{kT} = \frac{\partial P}{P} \Rightarrow \frac{\mu}{kT} \Big|_{P_0}^P = \ln P \Big|_{P_0}^P$$

$$\mu(T, P) - \overset{\text{reference value}}{\mu(T, P_0)} = kT \ln \left(\frac{P}{P_0} \right)$$

$$\mu(T, P) = \mu^0(T) + kT \ln \left(\frac{P}{P_0} \right)$$

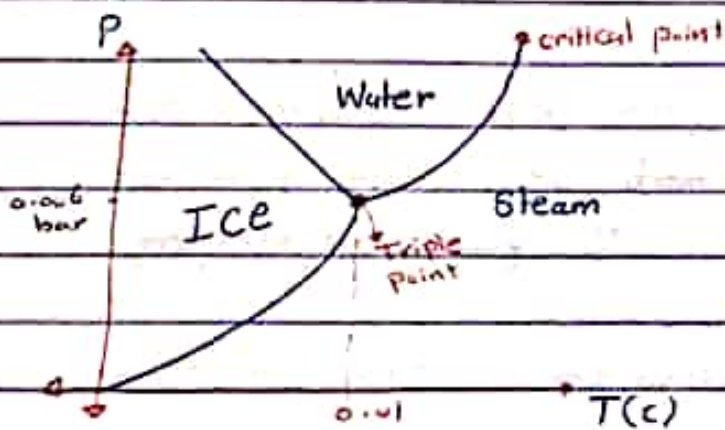
$\uparrow P \quad \uparrow \mu$
 $\uparrow P \quad \uparrow \text{concent}$

& gas

Phase Transformations of Pure Substances

• **Phase Transformation**: a discontinuous change in substance properties as the environment is changed infinitesimally e.g. boiling

• **Phases**: different forms of substances e.g. Magnetic properties



phase diagram: a graph showing the equilibrium phases as a function of Temperature & pressure.

• lines represent conditions under which two different phases coexist in equilibrium.

• Liquid-Gas phase boundary always has a positive slope.

• **Critical point**: Almost no difference between liquid & gas

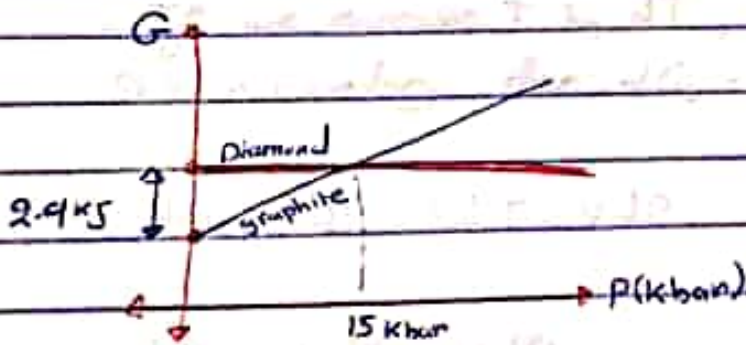
Diamond & graphite

- Carbon has two phases → Diamond
→ Graphite

دو مختلف کثافتوں کے حامل phase

- Both phases are solids, but with different crystal structure.
- At Ordinary Temperatures & pressure, graphite is more stable. So diamonds will change to graphite, but slowly. ∴

(Stable phase) is one with (lower Gibbs)



$$G = U + PdV - TS$$

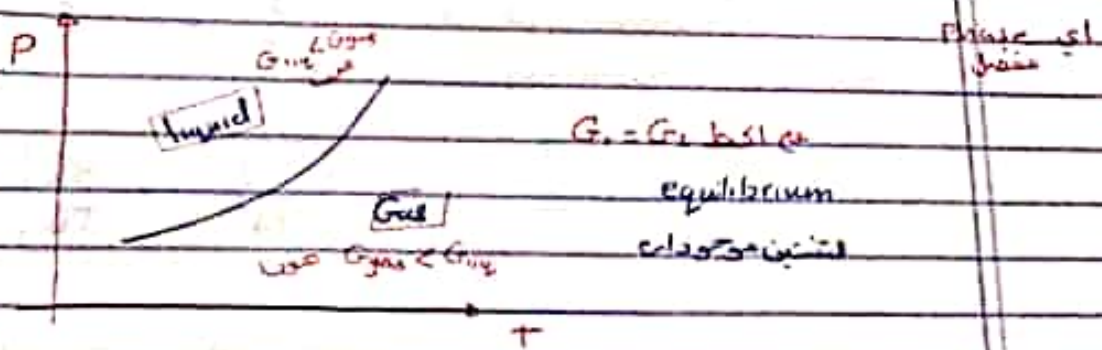
$$dG = \sum \mu_i dN_i + VdP - SdT$$

$$\left. \frac{\partial G}{\partial P} \right|_{T, N} = V$$

graphite
کثافت

U کی کمی ہے - T اور P میں کمی G

The Clausius - Clapeyron Relation



• We will examine phase boundary between liquid & gas (it works for any phases)

• At Boundary, $G_L = G_G$ & equilibrium

لینک ہندو $G_L = G_G$ جو ہے $T = dT$, T کا ہے $dG_L = dG_G$
 کی $G_L = G_G$ ہے $P = dP$, P

• If we increase T by dT , P by dP while still on boundary, then $dG_L = dG_G$

• $dG = \int dN - SdT + VdP$ (Assume $dN = 0$)

$$dG = -SdT + VdP$$

$$dG_L = -S_L dT + V_L dP = dG_G = -S_G dT + V_G dP$$

عن $dG = 0$ کی ہے

$$\frac{dP}{dT} = \frac{S_G - S_L}{V_G - V_L}$$

~~Dilat:~~

تكاليف التمدد في المواد الصلبة غير المتجانسة

$$S_g - S_L = \frac{L}{T} \quad , \quad L: \text{total latent heat per quantity of Material}$$

$$\frac{dP}{dT} = \frac{L}{T \Delta V}$$

Pb 5.32) $\rho_{ice} = 917 \frac{kg}{m^3}$ let $m = 1 \text{ kg ice}$
 $\rho_{water} = 1000 \frac{kg}{m^3}$

$$V_{ice} = 1.0905 \times 10^{-3} \text{ m}^3$$

$$V_{water} = 1 \times 10^{-3} \text{ m}^3$$

$$\Delta V = -0.0905 \times 10^{-3} \text{ m}^3$$

$$T = 273 \text{ K}$$

$$\Delta P = -13.5 \times 10^6 \text{ Pa}$$

Q5.36

The Van der Waal Model

• Liquid Gas System

• Ideal Gas : particles have zero volume
particles do not interact

$$PV = NKT$$

الغاز المثالي هو الذي لا يتفاعل بين جزيئاته ولا يملك حجم الجزيئات
الغاز الحقيقي يتفاعل بين جزيئاته ويملك حجم الجزيئات
يصحح القانون لاني

$$(P + a \frac{N^2}{V^2})(V - Nb) = NKT$$

لوضع الجزيئات
أقل حجم Nb

ب- أخرج جيز
مكثرا جده الجزيء

a & b : depend on Material

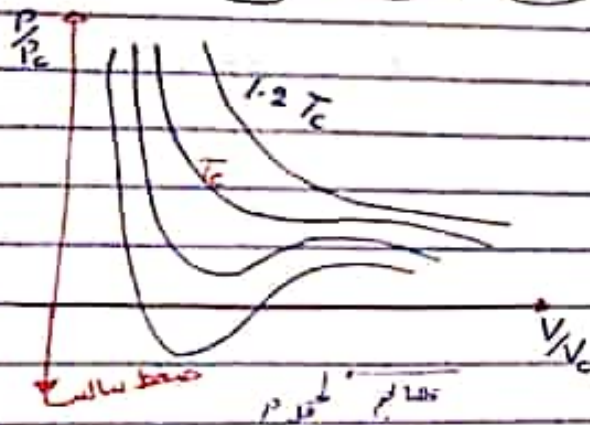
$$\Rightarrow P = \frac{NKT}{V - Nb} - a \frac{N^2}{V^2}$$

first correction : $V - Nb$: we consider each particle volume.

2nd correction : $P \rightarrow P - a \frac{N^2}{V^2}$ الضغط أقل

عشان نحصل على حجم معين يلزمنا ضغط أقل عشان نوصل للم اللى بدى اياها
لأنه لما يشربوا (ح) بعض جيز
قوى تجاذب بينهم

due to attraction forces between particles (when they get closer together), the gas becomes more compressible



T_c : critical Temp.
 V_c, P_c : Volume & pressure at T_c

• Behaviour at high Temp. is ok as expected by Ideal Gas Model.

• Behaviour at low Temperature Predicts strange Results
 (Compressing a fluid causes its pressure to decrease!)

Pb 5.48

⊗ $V_c = 3Nb$

⊗ $P_c = \frac{1}{27} \frac{a}{b^2}$

⊗ $kT_c = \frac{8}{27} \frac{a}{b}$

using $v = \frac{V}{V_c}$, $P = \frac{P}{P_c}$, $t = \frac{T}{T_c}$

$P = \frac{8t}{3v-1} - \frac{3}{v^2}$

المعادلة
 لتقدير
 الحجم

Van der Waal

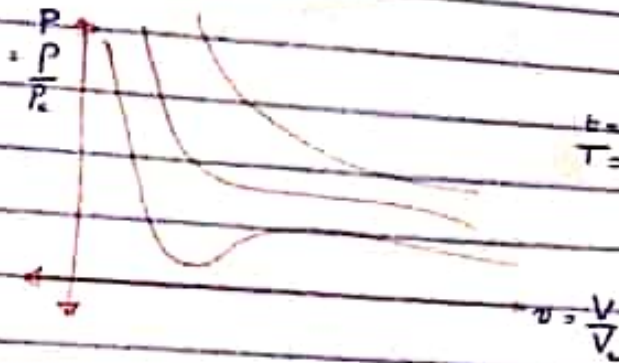
$$P = \frac{NkT}{V-N} - a \frac{N^2}{V^2}$$

dimensionless

$$P = \frac{8t}{3v-1} - \frac{3}{v^2}$$

dimensionless

$$\bar{P} = \frac{P}{P_c} \quad \bar{v} = \frac{V}{V_c}$$



$$t = 0.95$$

$$T = 0.95 T_c$$

T_c critical Temp

• We look at G free energy

• G determines equilibrium state at certain T, P .

$$dG = -S dT + V dP + \mu dN$$

At const T, N

$$\left(\frac{\partial G}{\partial V} = V dP \right) \Big|_{N,T}$$

const V
 \Rightarrow Helmholtz
 F

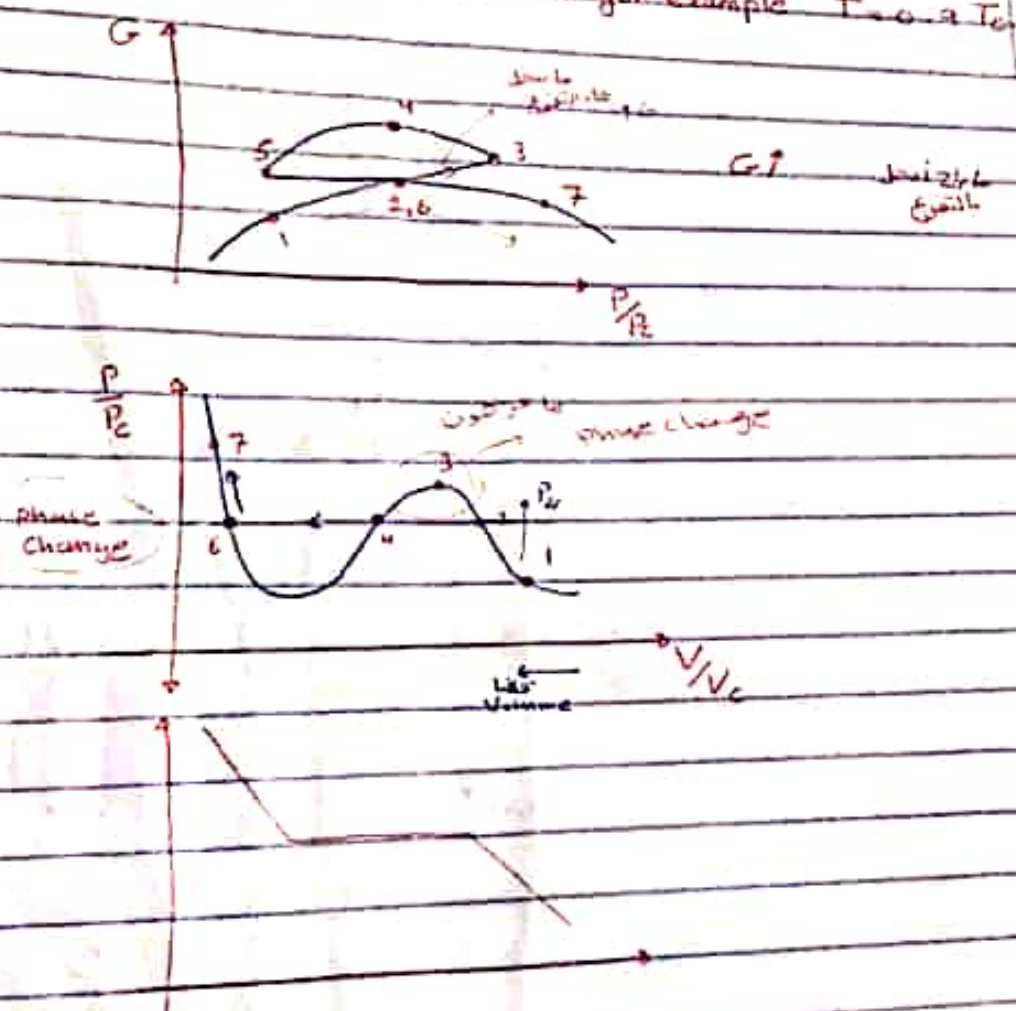
$$\left(\frac{\partial G}{\partial V} \right)_{N,T} = \left(V \frac{\partial P}{\partial V} \right)_{N,T}$$

$$P = \frac{NkT}{V-N} - a \frac{V^2}{N^2}$$

at T_c isothermal
 Isotherm.

$$G = -NkT \ln(V - Nb) + \frac{NkT(Nb)}{V - Nb} - 2a \frac{N^2}{V} + \text{const}(T)$$

Plot G vs. P & P vs. V at for example $T = 0.9 T_c$

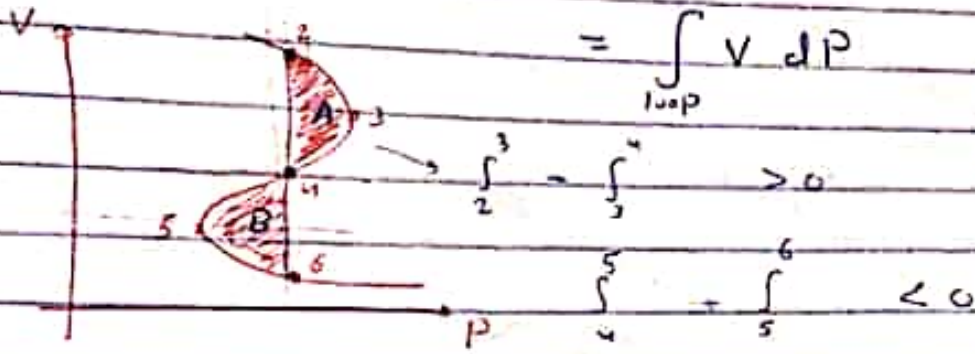


• Triangular Region (2-3-4-5-6) in G vs. P is due to unstable states; states have lower G :

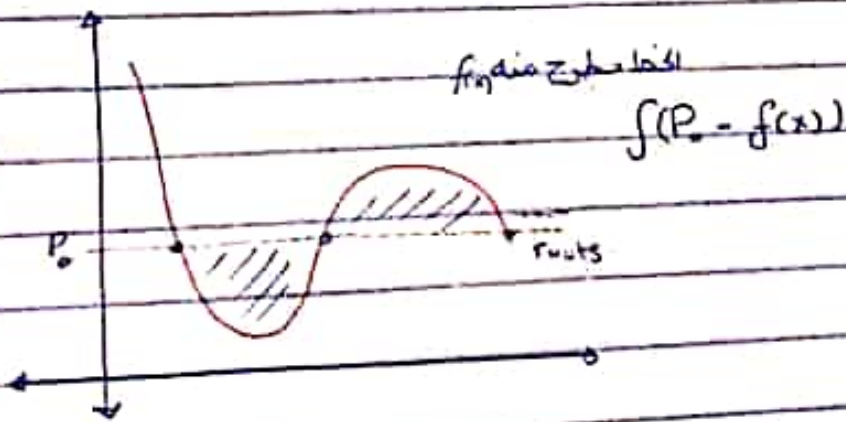
• As P is increased, system goes straight from 2 to 6. This is the phase transformation.

To get P at Phase Transformation note that

$$\int_{\text{loop } 2,3,4,5,6} dG = 0 = \int_{\text{loop}} \left(\frac{\partial G}{\partial P} \right)_T dP$$



$$|\text{Area } A| = |\text{Area } B|$$



Total integral areas (A & B) = 0 (Maxwell construction)

5.5) Dilute Solution

- Solvent (primary) & Solute (secondary)

- Dilute Solution : Solute \ll Solvent.

- Solute in a dilute solution behaves like an Ideal gas.

Solvent & Solute chemical potentials

- Start with a pure solvent, N_A molecules.

$$G = N_A \mu^0(T, P)$$

Pure solvent

Add one molecule B, with T & P const

$$dG = dU + PdV - TdS$$

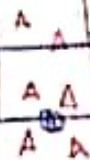
G is a state function

dU & PdV do not depend on N_A

dS depends on N_A

dG
is a state function
الزينة والألمنة

- The place where we put B matters



$$\Rightarrow dS = k \ln N_A + (\text{term independent of } N_A)$$

$$dG = f(T, P) - kT \ln N_A$$

• لا يقسم N_A
 (أي انيسوتا، واناسية
 بونه والاصروف)

• If we add Two B particles

$$dG = 2f(T, P) - 2kT \ln N_A - (-kT \ln 2)$$

لا يقسم
 Entropy -
 multiplicity
 microstates

• If we add N_B molecules

$$dG = N_B f(T, P) - N_B kT \ln N_A + kT \ln N_B!$$

$$dG = N_B f(T, P) - N_A kT \ln N_A + kT N_B \ln N_B - kT N_B$$

أو $N_B \ll N_A$ $dG = 0$ (أي انيسوتا) من لا يتم تغيير G

$$G_1 = G_0 + dG$$

$$G = N_A \mu_0(T, P) + N_B f(T, P) - N_B kT \ln N_A + kT N_B \ln N_B - kT N_B$$

Valid if $N_B \ll N_A$

- $\mu_A = \left(\frac{\partial G}{\partial N_A} \right)_{T,P,N_B} = \mu^{\circ}(T,P) - \frac{N_B kT}{N_A}$

- $\mu_B = \left(\frac{\partial G}{\partial N_B} \right)_{T,P,N_A} = f(T,P) - kT \ln N_A + kT \ln N_B + \frac{N_A kT}{N_B} - kT$

- $\mu_B = f(T,P) + kT \ln \frac{N_A}{N_B}$

could be written instead of Molality

molarity $m = \frac{\text{moles of solute}}{\text{kg. of solvent}}$

$$m = \frac{N_B}{N_A}$$

$$\mu_B = \mu^{\circ}(T,P) + kT \ln m_B$$

μ° , chemical potential at $m_B = 1$

intensive

IS G Extensive?

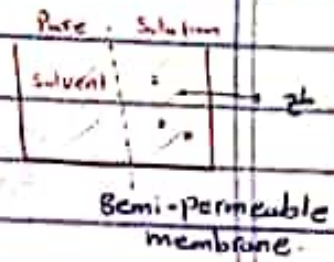
$$G = N_A \mu_A(T,P) + N_B \mu_B(T,P) = N_A \mu^{\circ}(T,P) - N_A \frac{N_B kT}{N_A} + N_B \left[f(T,P) + kT \ln \frac{N_A}{N_B} \right] = N_A \mu^{\circ}(T,P) - N_B kT + N_B f(T,P) + N_B kT \ln \frac{N_A}{N_B}$$

intensive

G energy (conservation) (10 + 10)

1) Osmotic Pressure

- Membrane only allows solvent to pass



Chemical potential

$$\mu_{A, \text{pure}} = \mu_0(T, P)$$

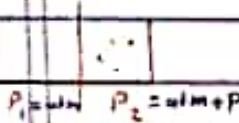
البيكروبيوتنسيال
ذاتة محبة

$$\mu_{A, \text{solution}} = \mu_0(T, P) - \frac{N_A kT}{N_A}$$

N_A
عدد جزيئات المذيب
في المحلول الممتزج
(Pure)

- Particles of solvent flow from pure \rightarrow solution

2) How do we stop Osmosis?



منه
نقل المذيب

One way is to add pressure on solution side until μ equilibrate

$$\mu_0(T, P_1) = \mu_0(T, P_2) - \frac{N_A kT}{N_A} \quad \text{--- 1}$$

- If the two pressures are not too different then

$$\mu_0(T, P_2) \approx \mu_0(T, P_1) + (P_2 - P_1) \frac{\partial \mu_0}{\partial P}$$

expansion

Eq 1

$$\mu_0(T, P_1) = \mu_0(T, P_2) - \frac{N_B kT}{N_A}$$

8

$$\text{Eq 2) } \mu_0(T, P_1) - \mu_0(T, P_2) = - (P_2 - P_1) \frac{\partial \mu_0}{\partial P}$$

$$(P_2 - P_1) \frac{\partial \mu_0}{\partial P} = \frac{N_B kT}{N_A}$$

اداء صوتي
 تغير في الضغط
 كما ان يكون P_2

How do we get $\frac{\partial \mu_0}{\partial P}$?

$$\mu = \frac{G}{N} \quad \& \quad \left. \frac{\partial G}{\partial P} \right|_{T, N} = V$$

$\frac{\partial \mu_0}{\partial P}$

$$\frac{\partial \mu_0}{\partial P} = \frac{V}{N} = \frac{\text{Volume}}{\text{Solvent Molecules}}$$

But, the solution is dilute.

$\frac{V}{N}$ is the same on both sides.

$$(P_2 - P_1) \frac{V}{N_A} = \frac{N_B}{N_A} kT \Rightarrow (P_2 - P_1) = \frac{N_B}{V} kT$$

$$P_2 - P_1 = \frac{n_B R T}{V}$$

ΔP : osmotic pressure

Exp 2) Inside a cell, we have 200 H₂O per each molecule of other types; ions, sugars

مثال 2

N_B

تزيد P_o الى
لازم اقلها
عنا ان وقت

الماء الا في

$$\Delta P = \frac{n_B R T}{V} = \left(\frac{1 \text{ mol}}{200 \text{ mol}} \right) (8.3) (300) \frac{1}{V}$$

1 mol of H₂O \leftarrow 18g

$$V = \left(\frac{18 \text{ cm}^3}{1 \text{ mol}} \right) \left(\frac{1 \text{ mol}}{100 \text{ cm}^3} \right)^3 =$$

$$\Delta P = \frac{300}{200} (8.3) \left(\frac{100 \text{ cm}^3}{18 \text{ cm}^3} \right) = 6.9 \times 10^5 \text{ N/m}^2$$

⊕ Boiling & Freezing points

Consider a dilute solution at its boiling point, in equilibrium with its gas phase



- No solute in gas phase, we consider only the solvent

At equilibrium

عند التوازن

$$\mu_{A(lq)} [T, P] = \mu_{A(gas)} [T, P]$$

عند التوازن
في شروحي

- $\mu_0(T, P) - \frac{N_0 kT}{N_A} = \mu_{gas}(T, P)$

- We expand each μ about a nearby point where the pure solvent would be in equilibrium

⊕ let us keep T const & vary P

عند تغير الضغط عند ثابت الحرارة
ونغير للثاني عنده
تغير في شروحي

- let P_0 be vapor pressure of pure solvent at T

$$\mu_0(T, P_0) = \mu_{gas}(T, P_0)$$

$$\mu_0(T, P) - \frac{N_B}{N_A} kT = \mu_{\text{gas}}(T, P)$$

$$\mu_0(T, P_0) + (P - P_0) \frac{\partial \mu_0}{\partial P} - \frac{N_B}{N_A} kT = \mu_{\text{gas}}(T, P) + (P - P_0) \frac{\partial \mu_{\text{gas}}}{\partial P}$$

$$\frac{\partial \mu_0}{\partial P} = \frac{V}{N}$$

$$(P - P_0) \left(\frac{V}{N} \right)_{\text{liquid}} - \frac{N_B}{N_A} kT = (P - P_0) \left(\frac{V}{N} \right)_{\text{gas}}$$

$$NkT = PV \Rightarrow$$

$$\frac{V}{N} = \frac{kT}{P}$$

V_{liq} : negligible

$$-\frac{N_B}{N_A} kT = (P - P_0) \left(\frac{V}{N} \right)_{\text{gas}}$$

$$-\frac{N_B}{N_A} kT = (P - P_0) \left(\frac{kT}{P_0} \right)$$

$$\frac{P}{P_0} = 1 - \frac{N_B}{N_A}$$

Raoult's Law

Now, hold the pressure fixed & solve for the shift in temp. needed to maintain equilibrium in the presence of the solute.

$$(T - T_0) = \frac{n_B R T_0^2}{L}$$

L: latent heat of Vaporization

Exp) Seawater

1 kg contains 35 g of NaCl

$$(T - T_0) = \frac{n_B R T_0^2}{L} = \frac{(1.2 \text{ mol}) (8.3) (373)^2}{2960 \text{ kJ}}$$

$$= 0.6 \text{ K}$$

$$\text{Boiling } T = T_0 + 0.6 \text{ K} = 100.6 \text{ }^\circ\text{C}$$

$$= 373.6 \text{ K} = 100.6 \text{ }^\circ\text{C}$$

$$n = \frac{\text{mass}}{\text{molar mass}}$$

$$= \frac{35}{58.5}$$

$$= 0.597$$

35 g of NaCl dissolves into 35/29 moles of ions.

To compute the Vapor pressure at given temp.

1 kg H₂O contains $\frac{1000 \text{ mole H}_2\text{O}}{18}$

$$\frac{\Delta P}{P_0} = \frac{-N_B}{N_A} = \frac{-1.2 \text{ mol}}{56 \text{ mol}} = -0.029$$