Fundamentals of Distribution Separations (I)

(01/09/15)

1. Introduction to Chemical Separation

2. Principles of distribution equilibria
-- Driving force for separative displacement

3. Intermolecular interactions
-- Major factors controlling equilibrium between phases

This is the base for understanding chemical separations such as chromatography and gel electrophoresis.

1. Introduction to Chemical Separations

a. The essential feature of separations:

b. Driving force for separative transport

c. Limitations for separation

d. Analytical and Preparative Separations

What is Chemical Separation? (I)

1. A complete separation of a mixture of chemical species:

$$(a + b + c + d + e + \ldots) \longrightarrow (a) + (b) + (c) + (d) + (e) + \ldots$$

2. A partial separation of a mixture of chemical species:

$$\begin{tikzcd}
 & (a) + (b + c + d + e + \ldots) \\
(a + b + c + d + e + \ldots) \arrow[ur] \arrow[dr] & \\
 & (a + b) + (c + d + e) + \ldots
\end{tikzcd}$$

3. The essential feature of separations:

Components must be transported and redistributed in space in order to realize the goals of the separative operation.

What is Chemical Separation? (II)

4. The transport basics do not stand alone:

- **(a) Equilibrium (driving force),**
- (b) The macroscopic, microscopic, and molecular structure of the system
- (c) The details of flow
- (d) Mechanics of sample handling

5. Limitations:

- **(a) Physical limitations: parameter controlling (e.g., T, P)**
- **(b) Chemical limitations:**
  - (i) equilibrium,

$$A_1 \overset{k}{\rightleftarrows} A_2$$

What is Chemical Separation? (III)

(ii) thermodynamic limitations: the second law of thermodynamics

Spontaneous direction of change: Entropy: $\Delta S > 0$ for an isolated system

$$(a) + (b) + (c) + (d) \quad \underset{\text{Separation}}{\overset{\text{Mixing } (\Delta V=0)}{\rightleftarrows}} \quad (a + b + c + d)$$

Spontaneous direction of change: Gibbs free energy: $\Delta G < 0$

$$\Delta G = \Delta H - T\,\Delta S$$

Enthalpy: $H = U + PV$

The first law of thermodynamics $\longrightarrow$ Internal energy: $\Delta U = q + w$

(a) external work, (b) heat, and (c) dilution

$$(a) \xrightarrow{\text{dilution}} (\quad a \quad)$$

$$\boxed{\text{Dilution: } \Delta S = n\,R\,\ln \frac{V_{(\text{final})}}{V_{(\text{initial})}}}$$

Question:

Calculate the entropy change that accompanies the separation of four oligonucleotides from one another in an aqueous containing 0.1 μmole of each. When separated, each component occupies one-quarter of original volume. Deduce from your results whether or not the separation is thermodynamically spontaneous.

four oligonucleotides: (1) AAA-TCA-GA; (2) AGA-TAC-GAT-ATA;
(2) ATA-CAC-TGT-AGA-TTT-CTA; (4) AAC-CTC-GTT-AGA-TCC-CTA-TCA

$$(a) \xrightarrow{\text{dilution}} (\quad a \quad)$$

$$\boxed{\text{Dilution: } \Delta S = n\, R \ln \frac{V_{(final)}}{V_{(initial)}}}$$

What is Chemical Separation? (IV)

6. No absolute separations

(1) Separation limitations
(2) Detection limitations

7. General methods

(1) Named after underlying forces or phenomena:
extraction, adsorption, crystallization, precipitation, ion exchange, diffusion, sedimentation, centrifugation.

(2) Named after the forms of operation:

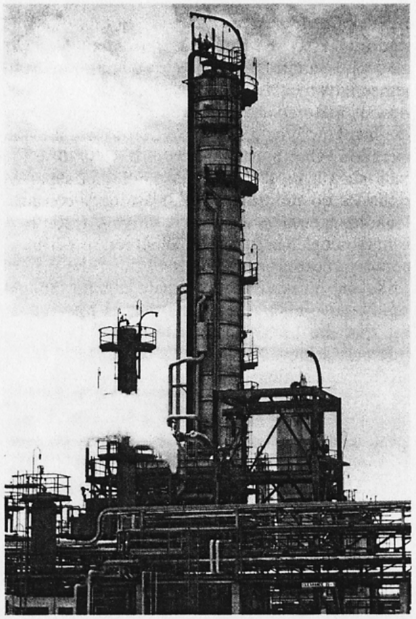
Chromatography, distillation, zone melting, filtration, dialysis, elutriation, field-flow fractionation, electrostatic precipitation.

(3) Both
Adsorption chromatography, ion exchange chromatography, extraction chromatography

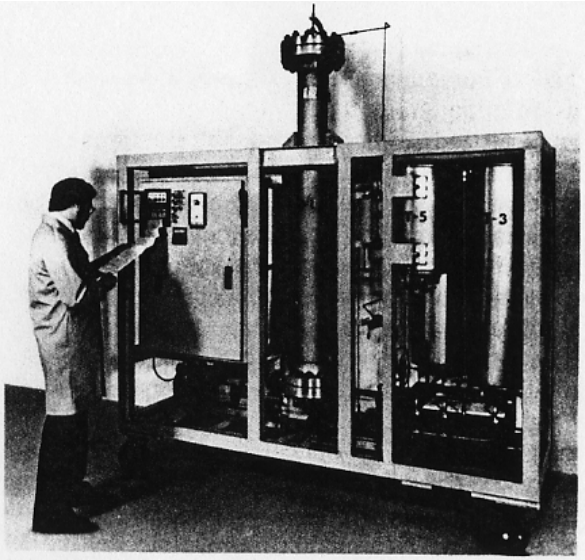
Analytical and Preparative Separations (I)

1. General goals of separation: preparative and analytical

2. Preparative separation: for drugs, fuels, metals, chemical feedstock for synthesis….
   Characteristics: (i) continuous in operation and (ii) large in scale
      distillation, extraction, smelting, (many tons per day)
      preparative liquid chromatography (biotechnology industry).



Crude fractionation tower at the Phillips Oil Refinery in Woods Cross, Utah. In this crude fractionator, 25,000 barrels per day of incoming crude oil is divided into six fractions by distillation. (Photo by Alexis Kelner.)



Preparative scale liquid chromatography unit with 6 ft (1.8 m) long column (in center) having an inner diameter of 6 in (15 cm). Up to 2 L of sample solution can be injected and processed in a single 90-min run. (Courtesy Thomas J. Filipi and Whatman Chemical Separation Division.)

Analytical and Preparative Separations (II)

2. Analytical separations:

Goal: understanding of mechanisms of separation, sample analysis, and
for subsequent detection.

Characteristics: (i) High purity and (ii) small scale

☺**Chromatography techniques**

(i) A physical separation technique

(ii) Components partition between two phases:
Stationary phase: does not move
Mobile phase: does move

(iii) Solutes separated in the two phases due to differences in how they interact with the phases.

Group Projects

A. Michelle Reid and Robin Kemperman
Quantitative detection of Hg in fish

B: Weijia Niu and Jiamin Liang

Rapid detection of HIV in blood samples

C. Emily Louise Gil and Jeremy Koelmel

Detection of prostate cancer

D**. Qiao Ruan and Juliette Experton.**

Diagnosis of brain-eating amoeba infections

E. Song Yang and Yindong

Detection of single-nucleotide a single human cell

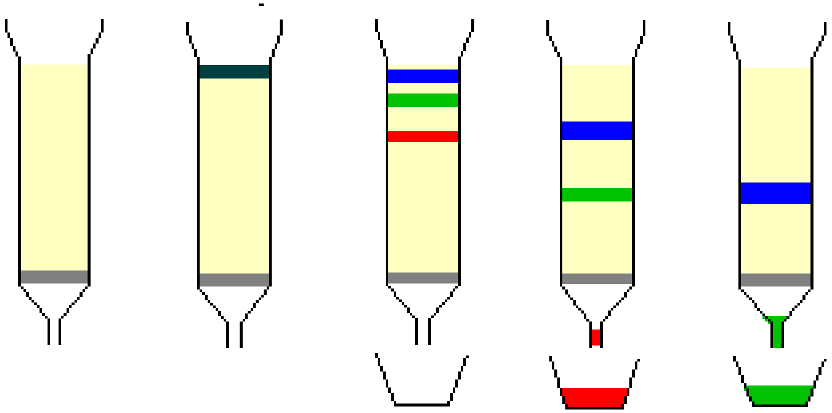
F. Kaitlyn Flower; Xigao Chen

Real-time measurement of the level of a specific m-RNA in single cells

2. Principles of distribution equilibria
-- Driving force for separative displacement

Two Important Classes of Equilibrium

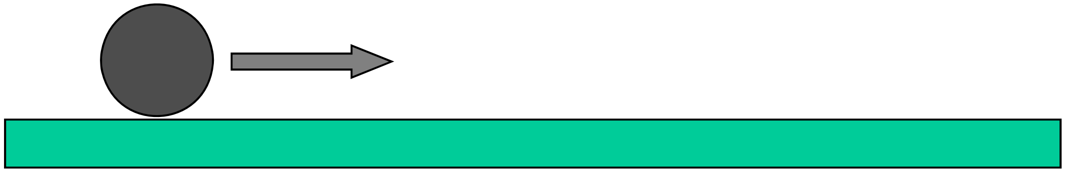
LC



(a) Mechanical equilibrium: the resting place of macroscopic bodies

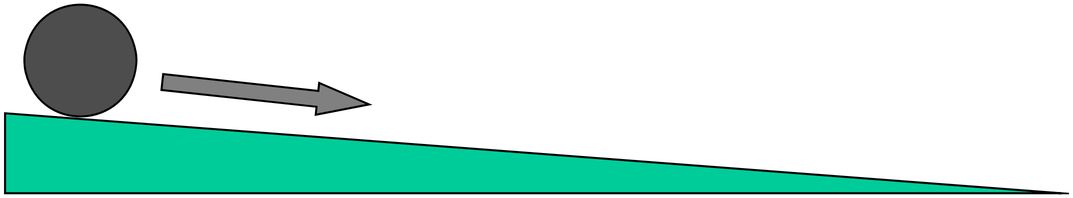
(b) Molecular equilibrium: the spatial distribution of molecules and colloids at equilibrium

Mechanical Equilibrium



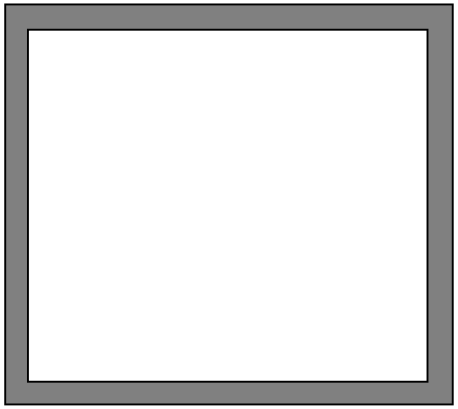
1. With macroscopic bodies, it is unnecessary to worry about the thermal (Brownian) motion, which greatly complicates the equilibrium in microscopic (molecular) systems.
2. Entropy effect is negligible
3. Mechanical equilibrium is subject to the simple criterion (no balanced forces)

$$\frac{dp}{dx} = 0\text{, potential energy p}$$



$$\frac{dp}{dx} \neq 0$$

Molecular Equilibrium in Closed Systems (I)



A closed system is one with boundaries across which no matter may pass, either in or out. However other changes may occur, including expansion, contraction, heating and cooling.

$dU = q + w$ .... the first law of thermodynamics

$w = -p * dV$

$dS \geq q / T$ .... the second law of thermodynamics

$dU \leq T * dS - p * dV$

$G = H - TS = U + pV - TS$

$dG \leq -S * dT + V * dP$

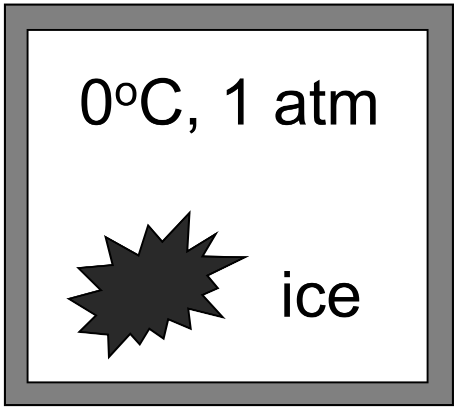
Molecular Equilibrium in Closed Systems (II)

$$dG \le -S * dT + V * dP$$

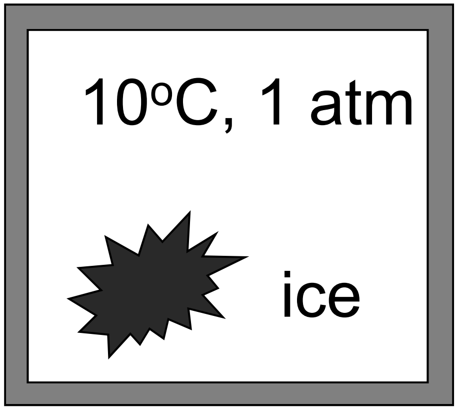
At the typical separation conditions, T and p are constant.

Then, $dG \le 0$

$dG = 0$, ………… molecular equilibrium

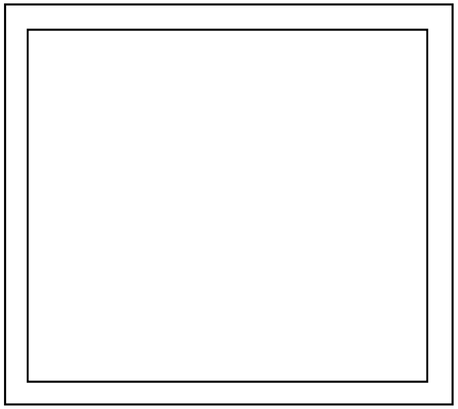


Ice-water equilibrium
Reversible, dG = 0



Spontaneous irreversible
Melting, dG < 0.

Molecular Equilibrium in Open Systems (I)



<u>An open system</u> is one which can undergo all the changes in the close system. In addition, it allows mass transfer across its boundaries.

$dG = -S * dT + \mathrm{V} * dP$ Equilibrium point for a close system

$$dG = \left(\frac{\text{ə}G}{\text{ə}\, n_i}\right)_{\mathrm{T,\ p,\ n_i}} dn_i$$

dn_i mole of *i* molecules enter the system, *T* & *p* are constant,

$$\mu_i = \left(\frac{\text{ə}\, G}{\text{ə}\, n_i}\right)_{\mathrm{T,\ p,\ n_i}}$$

Chemical potential

$$dG = \mu_i\, dn_i$$

Molecular Equilibrium in Open Systems (I)

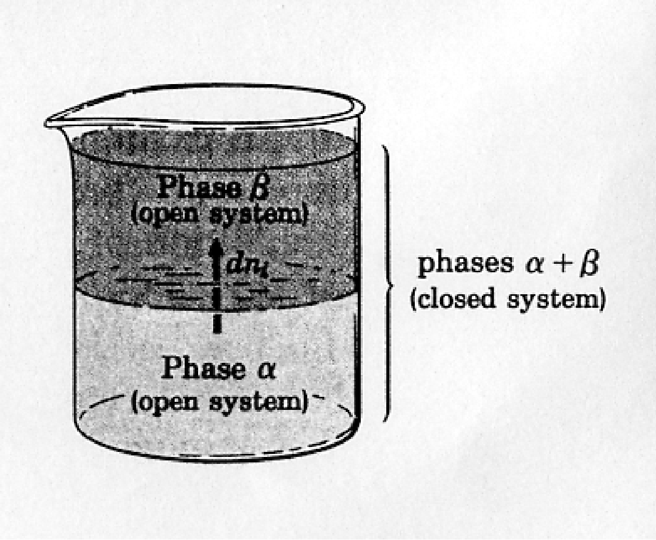
$dG = \Sigma\mu_i\, dn_i$

General equilibrium expression

$dG = -S * dT + V * dP + \Sigma\mu_i\, dn_i$ (if T, p are allowed to vary)

entering: *dn* is positive
Leaving: *dn* is negative

Two-phase open system:



$\alpha + \beta \longrightarrow$ a close system

For transfer component *i* from *α to β* at equilibrium

$$dG = dG^{\beta} + dG^{\alpha} = (\mu_i^{\beta} - \mu_i^{\alpha})\, dn_i = 0$$

$$\mu_i^{\beta} = \mu_i^{\alpha}$$

The Nature of Chemical Potential (μ_i)

Chemical potential, μ_i, for solute *i* in give phase depends on two factors (a) intrinsic thermodynamic affinity of solute to the phase, (b) dilution of Solute (affect μ_i through entropy: entropy of dilution).

$$\boxed{\mu_i = \mu_i^0 + \mathrm{RT}\ \ln c_i}$$

μ_i^0 : *standard-state chemical potential*

$$\left(\frac{c_i^\beta}{c_i^\alpha}\right) = \exp\left(\frac{-\Delta\mu_i^0}{RT}\right) \qquad \Delta\mu_i^0 = \mu_i^{0,\beta} - \mu_i^{0,\alpha}$$

$$K = \exp\left(\frac{-\Delta\mu_i^0}{RT}\right)$$ ***,distribution coefficient***

$$\begin{tikzcd}
 & \boxed{\mu_i = \mu_i^0 + \mathrm{RT}\ \ln \gamma_i c_i} \\
\boxed{\mu_i = \mu_i^0 + \mathrm{RT}\ \ln c_i} \arrow[ur] \arrow[dr] & \\
 & \boxed{\mu_i = \mu_i^0 + \mathrm{RT}\ \ln p_i}
\end{tikzcd}$$

γ_i *active coefficient*

for gas

Example: Sufficiently diluted, ethyl acetate has an equilibrium concentration at 20 °C in an isobutanol-rich phase that is 7.20 times higher than that in a water-rich phase (that is, the distribution coefficient K for isobutanol/H_2O is 7.20). What is the value of $\Delta\mu^o$ for the transfer of ethyl acetate from water to isobutanol solutions?

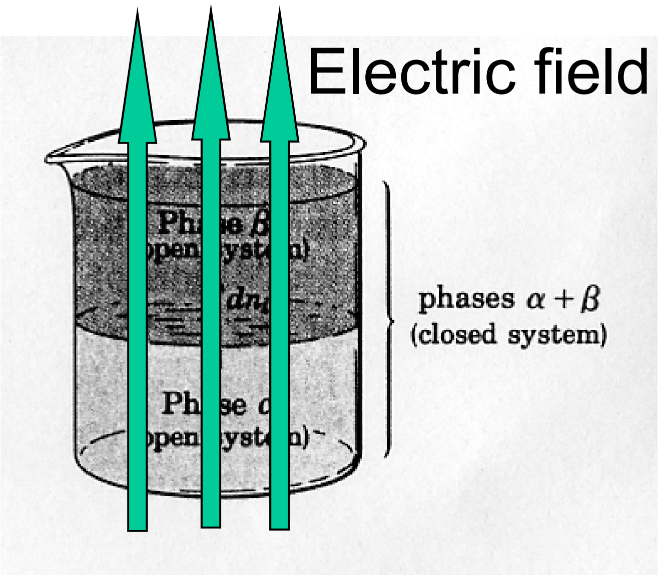
Equilibrium in External Fields

Common fields: electric, magnetic, sedimentation

$$dG = -S{*}\,dT + V{*}dP + \Sigma\mu_i\,dn_i$$

$$\Downarrow$$

$$dG = -S{*}\,dT + V{*}\,dP + \Sigma(\mu_i^{\text{int}} + \mu_i^{\text{ext}})dn_i$$



$$dG = dG^{\beta} + dG^{\alpha}$$

$$= (\mu_i^{\text{int},\,\beta} + \mu_i^{\text{ext},\,\beta} - \mu_l^{\text{int},\,\alpha} - \mu_i^{\text{ext},\,\alpha})\,dn_i = 0$$

$$\mu_i^{\text{int}} = \mu_i^{0} + \text{RT lnc}_{\text{i}}$$

Equilibrium in External Fields (II)

$$\left(\frac{c_i^\beta}{c_i^\alpha}\right) = \exp\left(\frac{-\Delta\mu_i^0 - \Delta\mu_i^{ext}}{RT}\right)$$

$$\Delta\mu_i^0 = \mu_i^{0,\beta} - \mu_i^{0,\alpha}$$

$$\Delta\mu_i^{ext} = \mu_i^{ext,\beta} - \mu_i^{ext,\alpha}$$

$$K = \exp\left(\frac{-\Delta\mu_i^0 - \Delta\mu_i^{ext}}{RT}\right)$$

Comparison: $\Delta\mu_i^0$ & $\Delta\mu_i^{ext}$

(1) Equal in a mathematical sense

(2) Dissimilar in a physical sense: changes at phase boundaries $\begin{cases} \Delta\mu_i^0\text{,abrupt} \\ \Delta\mu_i^{ext}\text{,continuous} \end{cases}$

The Nature of Chemical Potential (μ_i^0)

$$\Delta\mu_i^0 = \Delta\bar{H}_i^0 - T\Delta\bar{S}_i^0$$

$\Delta\bar{H}_i^0$, $\Delta\bar{S}_i^0$: the partial molar enthalpy and entropy under standard conditions.

$\Delta\bar{S}_i^0$: *randomness of the immediate molecular environment of a species*

For general separation system involving a partition of components between phases

$$\left|\Delta\bar{H}_i^0\right| \gg \left|T\Delta\bar{S}_i^0\right|$$

↓

Intermolecular interactions

What we have learnt:

1. Two Classes of Equilibria
2. Molecular Equilibrium in Closed Systems
3. Molecular Equilibrium in Open Systems
4. The Nature of Chemical Potential (μ_i)
5. Equilibrium in External Fields
6. Comparison of $\Delta\mu_i^0$ and $\Delta\mu_i^{ext}$
7. The Nature of Chemical Potential (μ_i^0)