Contents of Today

Review previous

Non-ideal Solution

Gibbs-Duhem Relation

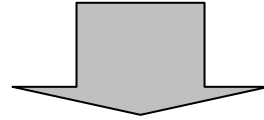Integrating the Gibbs-Duhem Equation

Dilute Solution and Colligative Properties

Review of today

Introduction 1：溶液？

Chemical changes among pure components and compounds

Solutions: elements or compounds dissolved in one another

何谓溶液？

一种物质以分子、原子或离子状态分散与另一种物质中所构成的均匀而又稳定的体系叫溶液。

高等学校教材，无机化学第三版，上册（ISBN 7-04-004581-8） 328页

布朗运动？

Many of the interesting properties of materials and many important chemical reactions take place

Thermodynamics of these solutions

Introduction 2

相变是物质由一个相向另一个相的传递过程
扩散是物质由高浓度区向低浓度区的传递过程
化学反应可以看作是物质由反应物向产物的传递过程

在传递过程中化学势将起决定作用。

在恒温恒压下， $$dG = \sum_i \mu_i dn_i$$

再由自由能判据 dG≤0 可得判据的另一形式（化学势判据）：

$$\sum_i \mu_i dn_i \le 0$$

在相变过程中物质i总是由化学势高的一相向转向化学势低的一相，直到两相中的化学势相等为止。而物质在两相中存在的化学势差 Δμ$_i$ 是物质传递的动力。

例子

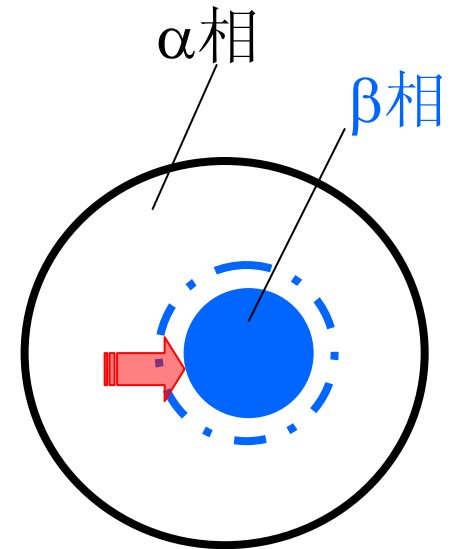在等温等压下，两相平衡是常见的，如复相黄铜（铜—锌合金）中α黄铜和β黄铜的平衡。设系统α 、β两相相接触，在等温等压下，若组分B（*例如铜*）有dn_B由α相进入β相，则α相中B组分减少dn_B ，而β相中B组分增加dn_B ；其吉布斯函数变化分别为：

$$dG^\alpha = \mu_B^\alpha(-dn_B) \qquad dG^\beta = \mu_B^\beta(dn_B)$$

总的吉布斯函数变化等于

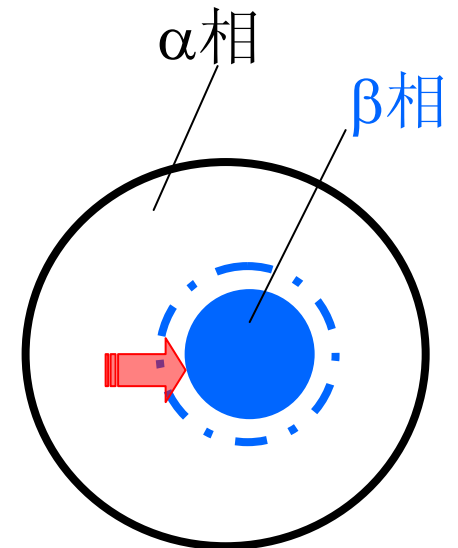$$dG = dG^\alpha + dG^\beta = (\mu_B^\beta - \mu_B^\alpha)(dn_B)$$

α相

β相

15:48:33

例子续1

系统达到平衡时，即 $dG = 0$

因为 $dn_B \neq 0$ 所以 $\boxed{\mu_B^{\beta} = \mu_B^{\alpha}}$

上式表明，对于多组分多相系统的平衡条件是："除系统中各相的温度和压力必须相等外，任一组分在各相中的化学势也必须相等。"即

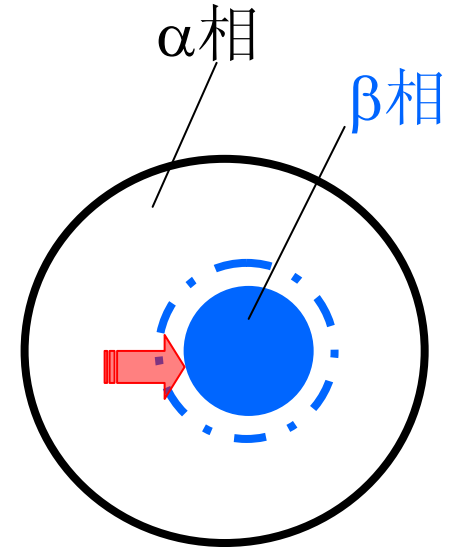$$\mu_B^{\alpha} = \mu_B^{\beta} = \cdots = \mu_B^{\gamma}$$

α相

β相

例子续2

若上述转移过程可以实现，则

$$dG = (\mu_B^\beta - \mu_B^\alpha)(dn_B) < 0$$

因为 $dn_B > 0$

所以

$$\mu_B^\beta < \mu_B^\alpha$$

组分B有dn_B由α相
进入β相

α相

β相

上式表明物质总是由化学势较高的相自发转移到化学势较低的相，直到该物质在两相中的化学势相等。

对比水与水位、电流与电势的关系，也有某种"势"的意思，所以称为化学势

化学势判据

$$\sum_B \mu_B dn_B \le 0 \qquad \sum_i \mu_i dn_i \le 0$$

这一判据式讨论具体的平衡规律、过程的方向与限度

P, V, Xi影响化学势

1，温度的影响

$$\left(\frac{\partial G}{\partial T}\right)_{P,x_i} = -S \qquad\qquad \underline{S}_{298}^0 = \int_0^{298} \frac{C_P}{T} dT$$

2，压力的影响   气相

$$\left(\frac{\partial G}{\partial P}\right)_{T,x_i} = V \qquad\qquad \underline{V} = \frac{RT}{P} \qquad\qquad d\underline{G} = RTd\ln P$$

3，组成的影响：偏摩尔Gibbs自由能

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Thermodynamic activity

Fugacity is defined for gases:

$$d\overline{G}_i = RTd(\ln f_i)$$

Thermodynamic activity of a component, i, is defined as:

$$\alpha_i \equiv \frac{f_i}{f_i^{\circ}}$$

f_i° The fugacity of the component i in its standard state.

The fugacity of a condensed phase is equal to the fugacity of the vapor phase in equilibrium with it.

The fugacity of the vapor is equal to the pressure of the vapor, if the vapor in equilibrium with the condensed phase is ideal.

Relative Partial Molar Quantities

Mixing of A and B to form a solution, the volume changes:

$$\Delta V_{mixing} = V_M = V_{final} - V_{initial}$$

V_M is the volume change upon mixing: 混合前后容量性质变化

$$V_M = n_A \overline{V}_A + n_B \overline{V}_B - n_A \underline{V}_A - n_B \underline{V}_B$$

$$V_M = n_A (\overline{V}_A - \underline{V}_A) - n_B (\overline{V}_B - \underline{V}_B)$$

$\boxed{\overline{V}_A^{rel}}$ $\boxed{\overline{V}_A - \underline{V}_A}$ The relative partial molar volume of A
The partial molar volume of A in solution relative to the molar volume of pure A.

$$V_M = n_A \overline{V}_A^{rel} + n_B \overline{V}_B^{rel}$$

Graphical Representation (5)

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$$\overline{G}_A^{rel} = \overline{G}_A - \underline{G}_A^\circ = RT \ln \alpha_A$$
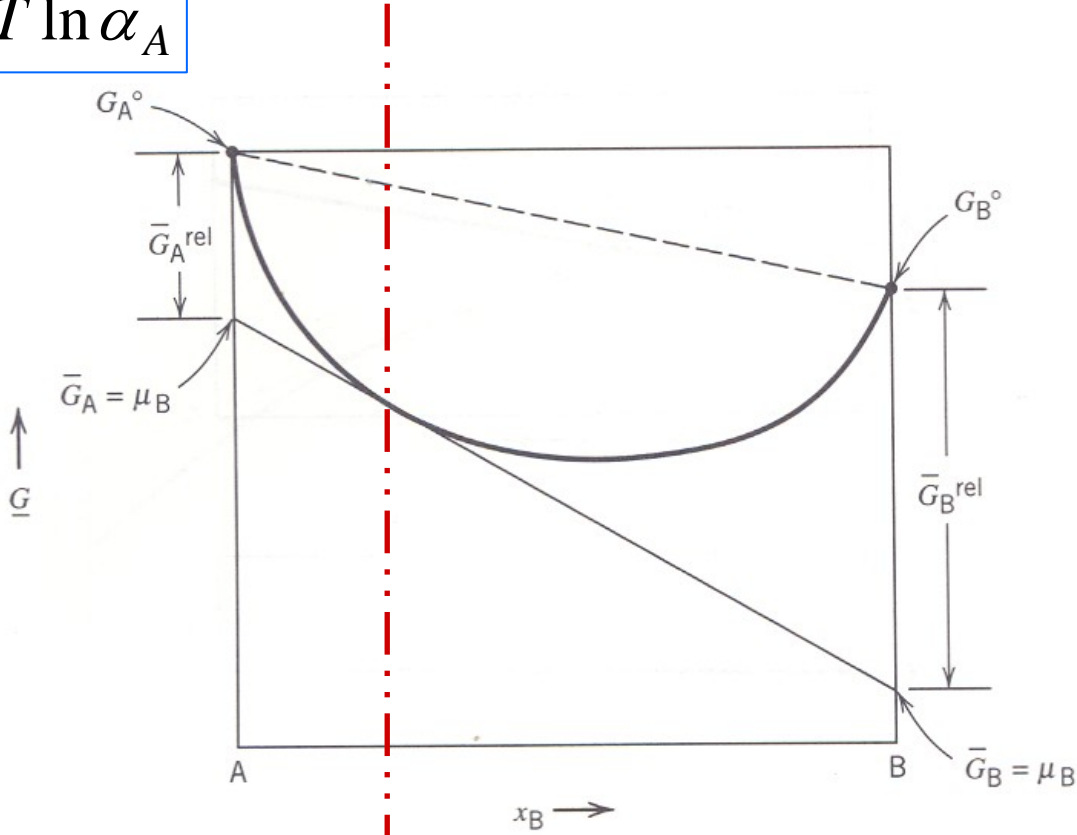

Figure 7.5 Plot of $\underline{G}$ versus x_B to show geometrical relationships between molar Gibbs free energy and mole fraction of B. (Note free choice of level for G_A° and G_B°.)

Relative Partial Molar Quantities (2)

$$V_M = n_A \overline{V}_A^{rel} + n_B \overline{V}_B^{rel}$$

For one mole of solution,

$$\underline{V}_M = x_A \overline{V}_A^{rel} + x_B \overline{V}_B^{rel}$$

U, F, G, H, S, V

The equations for variations of thermodynamic properties with temperature, pressure, and <u>so on apply to solutions as well as to pure components</u>.

$$d\overline{G}^{rel} = -\overline{S}^{rel} dT$$

$$\boxed{\overline{G}_A^{rel} = \overline{G}_A - \underline{G}_A^{\circ} = RT \ln \alpha_A}$$

Enthalpy of Mixing: Ideal Solution
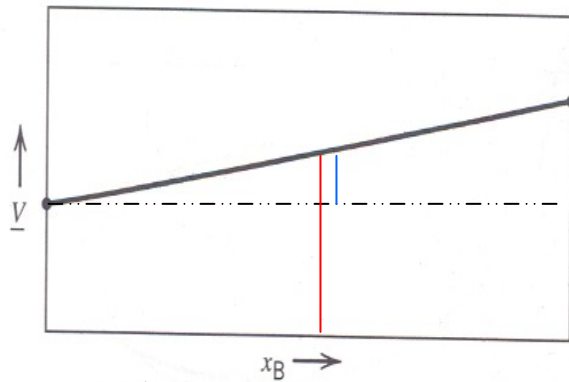
To summarize, for an ideal solution:

$$\underline{G}_M = RT\sum_i x_i \ln x_i \qquad\qquad \underline{H}_M = 0$$

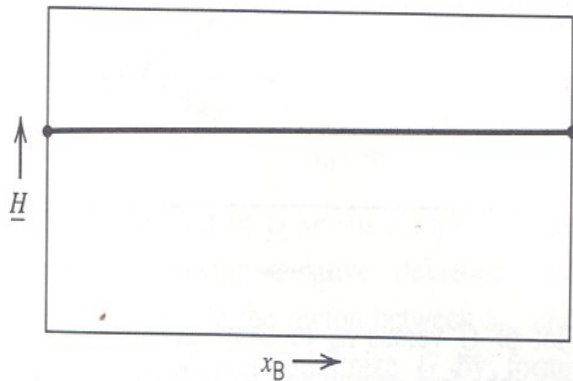$$\underline{S}_M = -R\sum_i x_i \ln x_i \qquad\qquad \underline{V}_M = 0$$
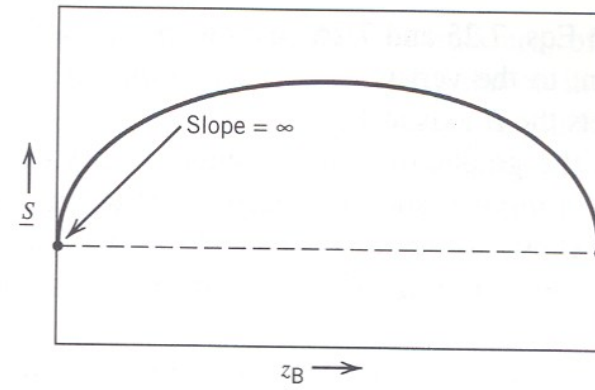
Line?

(a)

(b)

(c)

Slope = ∞

(d)

Slope = $-\infty$

T_1

T_2

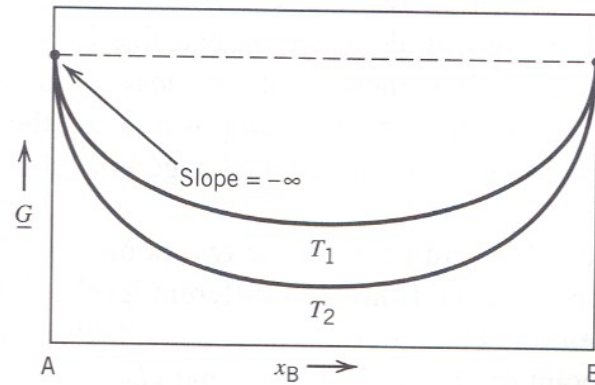**Figure 7.4** Molar properties for an ideal solution A–B: (a) volume of mixing, (b) enthalpy of mixing, (c) entropy of mixing, and (d) Gibbs free energy of mixing.

$$\underline{V} + x_A \left(\frac{\partial \underline{V}}{\partial x_B} \right)_{T,P} = \overline{V}_B$$

$$\underline{V} - x_B \left(\frac{\partial \underline{V}}{\partial x_B} \right)_{T,P} = \overline{V}_A$$
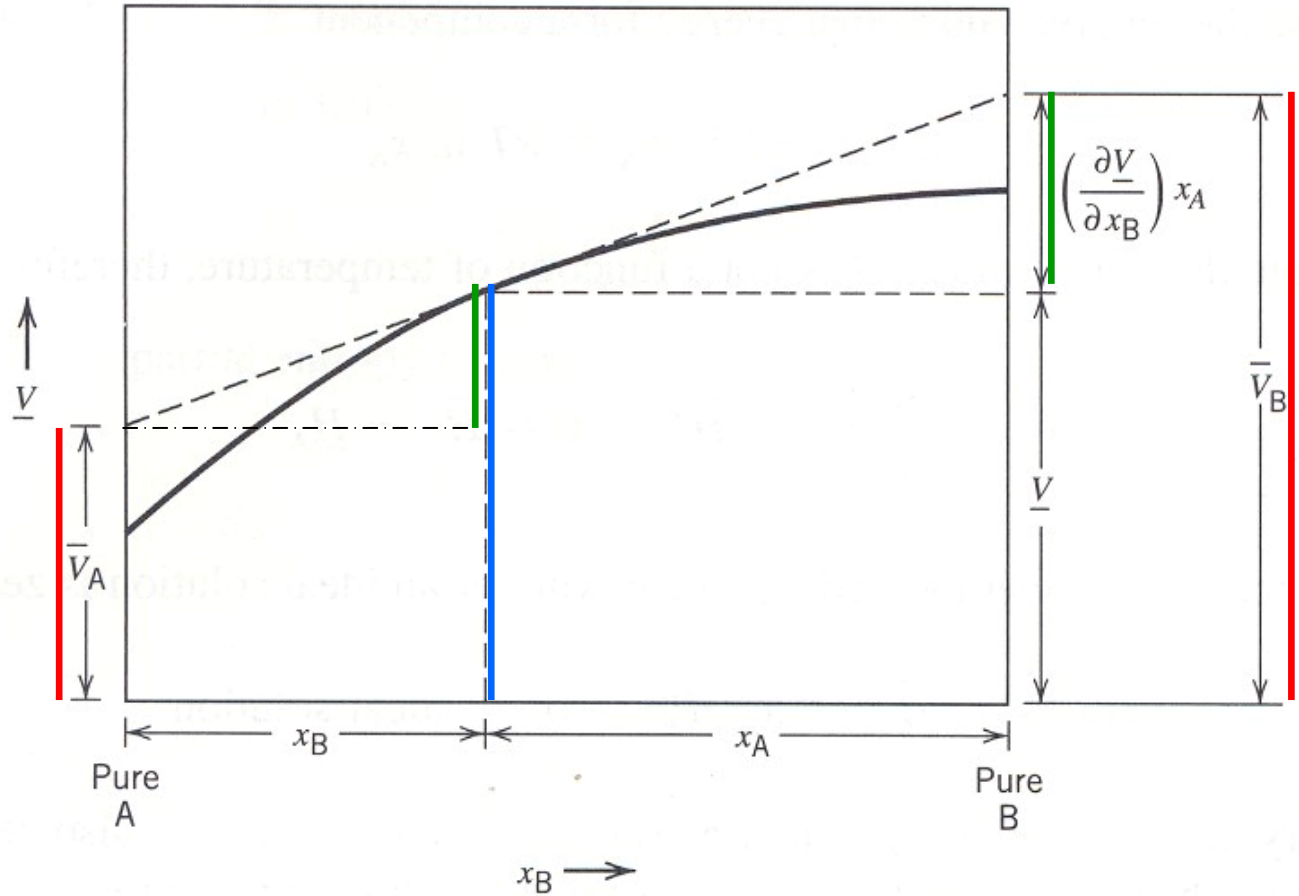

Figure 7.3 Plot of $\underline{V}$ versus x_B to show geometrical relationships in an A–B solution.

Non-ideal Solution: 非理想溶液

Activity coefficient: 活度系数

Gibbs-Duhem Relation：Gibbs-Duhem关系式

Dilute Solution：稀溶液

Colligative Properties：依数性

Osmotic Pressure：渗透压

Introduction

15:48:33

$$\underline{G}_M = RT \sum_i x_i \ln x_i$$

Slope = $-\infty$

T_1

T_2

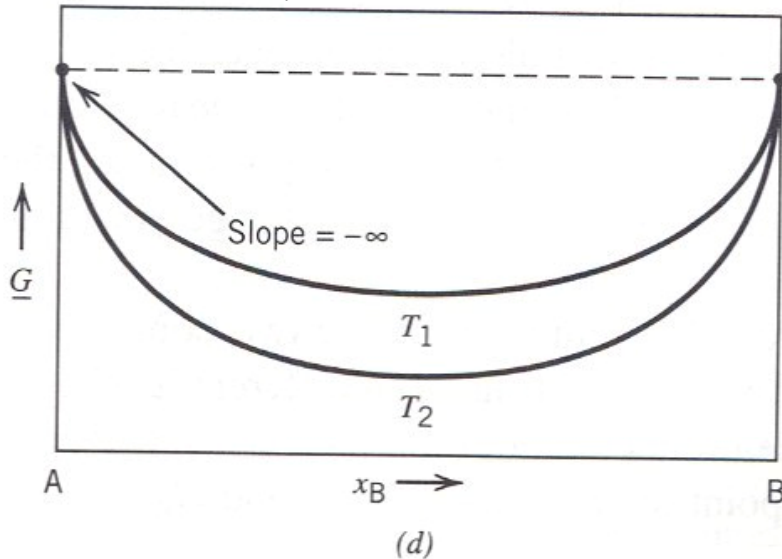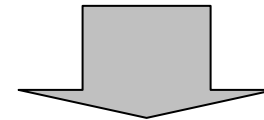$\underline{G}$

A $x_B \longrightarrow$ B

(d)

Figure 7.4 Molar properties for an ideal solution A–B: (a) volume of mixing, (b) enthalpy of mixing, (c) entropy of mixing, and (d) Gibbs free energy of mixing.

Ideal solution

Non-ideal solution: practical solution

Many forms

Non-ideal Solution (1)

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$$\underline{G}_M \neq RT \sum_i x_i \ln x_i$$

A single solution in this region is unstable relative to the mixture of solutions of x_{B1} and x_{B2}.

If equilibrium were attained, the single solution would decompose into two solutions because the Gibbs free energy change associated with such a decomposition is negative.
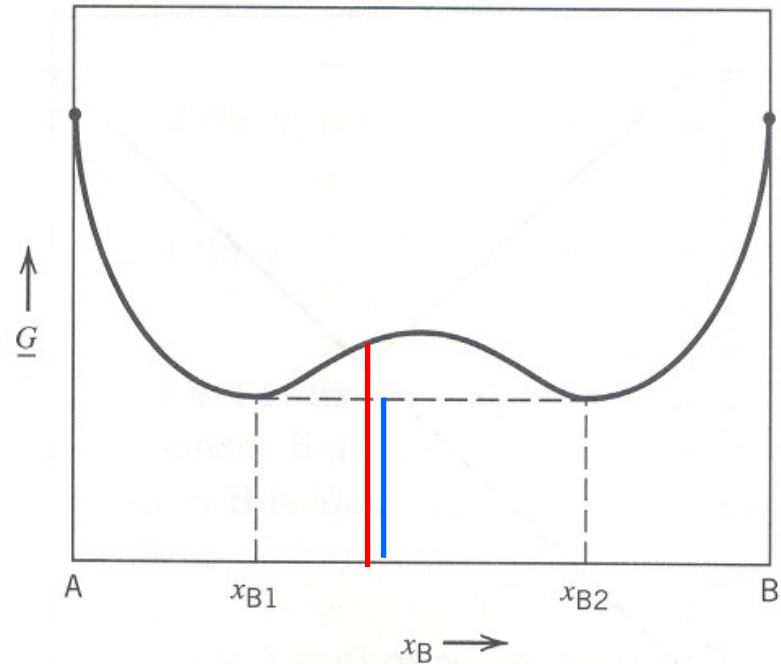
Figure 7.6 Plot of $\underline{G}$ versus x_B for a nonideal solution, showing positive deviations from Raoult's law. (In the region between x_{B1} and x_{B2}, the system can minimize G by forming mixtures of two solutions, x_{B1} and x_{B2}.)

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Non-ideal Solution (2)

$$\underline{G}_M \neq RT \sum_i x_i \ln x_i$$

Two immiscible materials

Materials A and B form no solutions

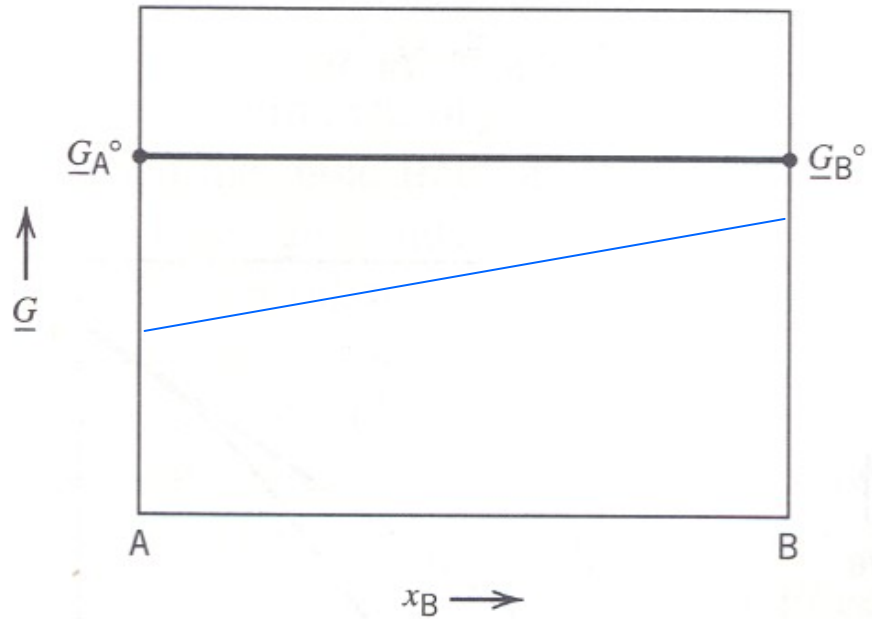**Figure 7.7** Plot of $\underline{G}$ versus x_B for mixtures of A and B, where A and B are immiscible.
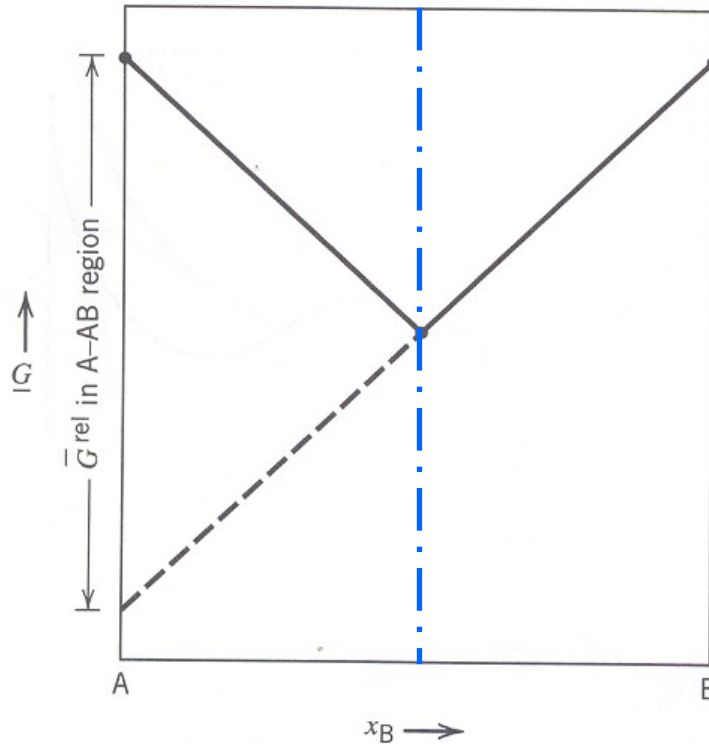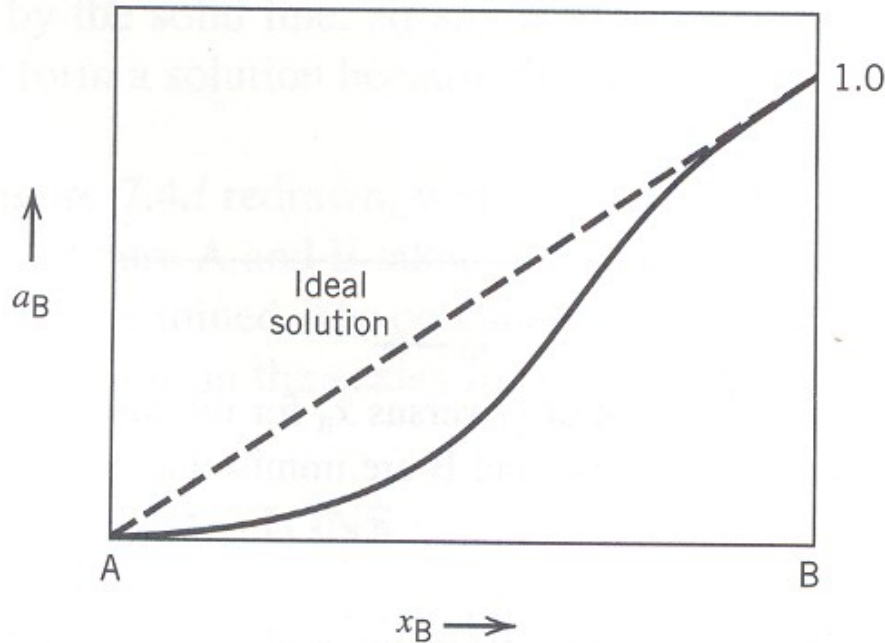
Non-ideal Solution (3)

A compound AB does not dissolve in either A or B.

Figure 7.8 Plot of $\underline{G}$ versus x_B in an A–B system when compound AB is formed.

$$\underline{G}_M \neq RT \sum_i x_i \ln x_i$$

Non-ideal Solution (4)

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$x_B=1$

$a_B=1$

$$\alpha_B = \gamma_B x_B$$

$$G_B = RT \ln \alpha_B = RT \ln(\gamma_B x_B)$$

a_B

Ideal
solution

A

B

$x_B \longrightarrow$

Figure 7.9 Plot of activity versus composition for a nonideal solution.

f_i

$f_i°$ 1.0

a_i

0

0
Pure $\frac{i}{1}$

0

$x_i \longrightarrow$

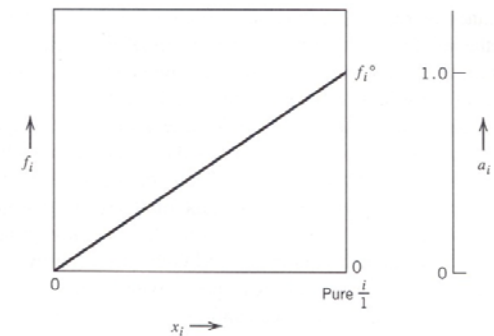**Figure 7.1** Fugacity of component i (f_i) and activity of component i (a_i) as a function of mole fraction (x_i) for an ideal solution.
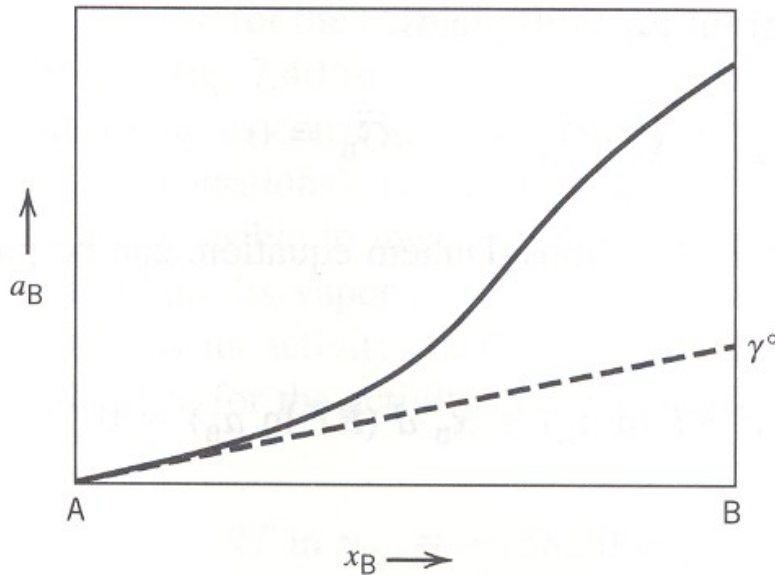
Non-ideal Solution (5)

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Figure 7.10 Extrapolation from the dilute region in a plot of activity versus composition for a nonideal solution.

$$\alpha_B = \gamma_B x_B$$

$$G_B = RT \ln \alpha_B = RT \ln(\gamma_B x_B)$$

实际溶液

理想

• 非理想

多种多样

稀溶液

规则溶液

等等

Gibbs-Duhem Relation (1)

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$$\underline{G} = x_A \overline{G}_A + x_B \overline{G}_B$$

Molar Gibbs free energy of A-B

$$d\underline{G} = \overline{G}_A dx_A + \overline{G}_B dx_B + x_A d\overline{G}_A + x_B d\overline{G}_B$$

$$G = G(n_A, n_B)_{T,P}$$

$$dG = \overline{G}_A dn_A + \overline{G}_B dn_B$$

$$d\underline{G} = \overline{G}_A dx_A + \overline{G}_B dx_B$$

A molar:

$$x_A d\overline{G}_A + x_B d\overline{G}_B = 0$$

Gibbs-Duhem equation

Gibbs-Duhem Relation (2)

More useful form:

Gibbs-Duhem equation

$$x_A d(RT \ln \alpha_A) + x_B d(RT \ln \alpha_B) = 0$$

$$d(\ln \alpha_A) = -\frac{x_B}{x_A} d(\ln \alpha_B)$$

If the activity of one component of a binary solution is known as a function of composition, then the activity of the other can be determined.

$$\ln \alpha_A = -\int_0^{x_B} \frac{x_B}{x_A} \frac{dx_B}{x_B} = -\int_0^{x_B} \frac{dx_B}{x_A}$$

Suppose the B behaves ideally.
From pure A to x_B.

$$dx_A = -dx_B$$

$$\ln \alpha_A = \int_1^{x_A} \frac{dx_A}{x_A} = \ln x_A$$

A behaves ideally.

$$\alpha_A = x_A$$

Gibbs-Duhem Relation (3)
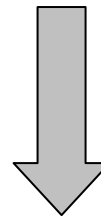
$$x_A d\left[\ln(\gamma_A x_A)\right] + x_B d\left[\ln(\gamma_B x_B)\right] = 0$$

Activity coefficients

$$x_A d(\ln \gamma_A) + x_B d(\ln \gamma_B) + \underline{x_A d(\ln x_A) + x_B d(\ln x_B)} = 0$$

$$0$$

$$x_A d(\ln x_A) = dx_A \quad \text{and} \quad x_B d(\ln x_B) = dx_B \quad \text{and} \quad dx_A + dx_B = 0$$

$$x_A d(\ln \gamma_A) + x_B d(\ln \gamma_B) = 0 \qquad d(\ln \gamma_A) = -\frac{x_B}{x_A} d(\ln \gamma_B)$$

If B is ideal; $\quad \gamma_B = 1 \quad$ or $\quad \gamma_A = cons\tan t$

$$x_A = 1 \quad a_A = 1$$

$$\gamma_A = 1 \qquad \boxed{\text{Ideal}}$$

$$\int_0^{\ln\alpha_A} d(\ln\alpha_A) = \int_{-\infty}^{\ln\alpha_B} -\frac{x_B}{x_A} d(\ln\alpha_B)$$

$$\ln\alpha_A = -\int_{-\infty}^{\ln\alpha_B} \frac{x_B}{x_A} d(\ln\alpha_B)$$

The case of copper-zinc alloys:

$$RT\ln\gamma_{Zn} = -38,300 x_{Cu}^2$$

$$d(\ln\gamma_{Cu}) = -\frac{x_{Zn}}{x_{Cu}} d\left(-\frac{38,300}{RT}x_{Cu}^2\right) = x_{Zn}\frac{2(38,300)}{RT}dx_{Cu}$$

Brass: copper - Zinc
The activity of zinc is easy to measure because zinc is volatile, and it is possible to measure its pressure in equilibrium with zinc-containing liquids or solids.

$$dx_{Cu} = -dx_{Zn}$$

$$\int_0^{\ln \gamma_{Cu}} d(\ln \gamma_{Cu}) = -\int_0^{x_{Zn}} \frac{2(38,300)}{RT} x_{Zn} dx_{Zn}$$

$$\ln \gamma_{Cu} = -\frac{38,300}{RT} x_{Zn}^2$$

Brass: copper - Zinc
The activity of zinc is easy to measre because zinc is volatile, and it is possible to measure its pressure in equilibrium with zinc-containing liquids or solids.

$$\int_{0}^{\ln \alpha_A} d(\ln \alpha_A) = \int_{-\infty}^{\ln \alpha_B} -\frac{x_B}{x_A} d(\ln \alpha_B)$$

$$\ln \alpha_A = -\int_{-\infty}^{\ln \alpha_B} \frac{x_B}{x_A} d(\ln \alpha_B)$$

避免活度系数从负无穷积分

$$d(\ln \gamma_A) = -\frac{x_B}{x_A} d(\ln \gamma_B)$$

$$\int_{0}^{\ln \gamma_A} d(\ln \gamma_A) = \ln \gamma_A = -\int_{\ln \gamma_B^\circ}^{\ln \gamma_B} \frac{x_B}{x_A} d(\ln \gamma_B)$$

起点：活度系数为常数

$$\int_{\ln \gamma_B^\circ}^{\ln \gamma_B} \frac{x_B}{x_A} d(\ln \gamma_B)$$

$\frac{x_B}{x_A}$

Henry's law region
$\gamma_B = \gamma_B^\circ$

$lu\gamma_B^\circ$

$\ln \gamma_B \longrightarrow$

Figure 7.12 Graphical integration of the Gibbs–Duhem equation.

- 稀溶液
溶剂符合Raoult定量，即理想溶液
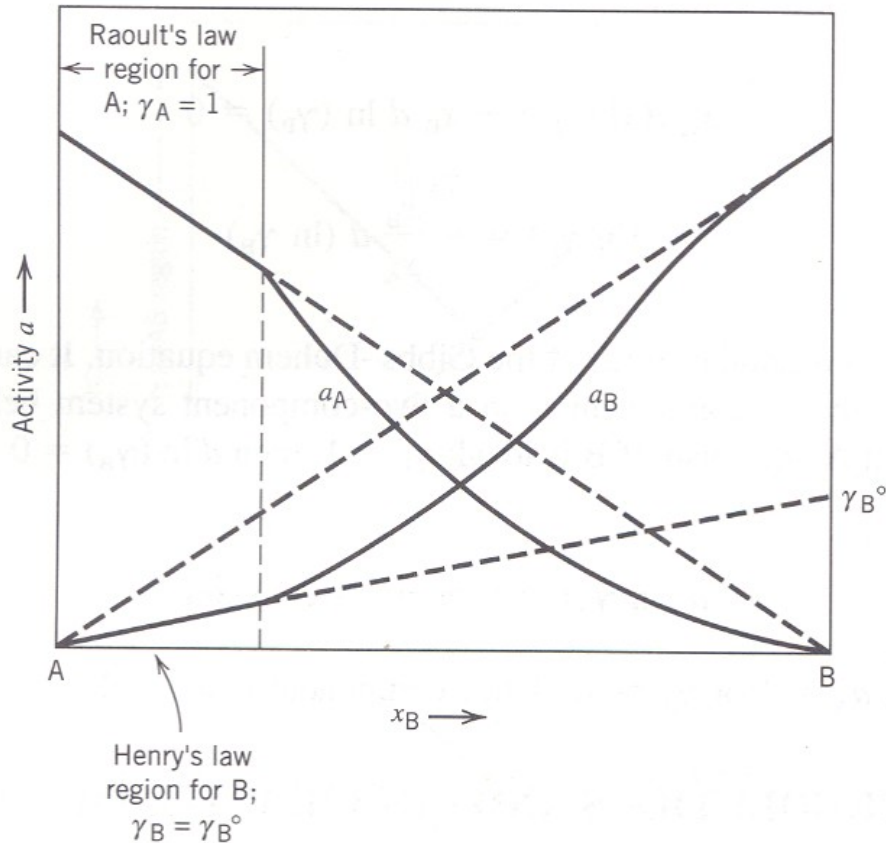溶质符合Henry定量，非理想，活度系数为常数

Figure 7.11 Henry's law and Raoult's law regions for the nonideal solution.

Henry's law region:

$$\gamma_B = \gamma_B^\circ \qquad d\left(\ln \gamma_B^\circ\right) = 0$$

$$\gamma_B^\circ = Cons \tan t$$

Raoult's law region:

$$\gamma_A^\circ = 1$$

$$x_A = 1, \ a_A = 1$$

Raoult's law and Henry's law

Raoult's law
1887年，经验定律， $P_A = P_A^* x_A \Rightarrow a_A = x_A$

"溶液中溶剂的蒸气压P_A等于同一温度下纯溶剂的蒸气压P^*_A与溶液中溶剂的摩尔分数x_A的乘积"

Henry's law
1803年，经验定律 $x_B = k'_{x,B} P_B \Rightarrow P_B = k_{x,B} x_B \not\Rightarrow \gamma_B = 1$

$$k_{x,B} ? P_B^*$$

"在一定温度下微溶气体在溶液中的平衡组成与该气体的平衡气相分压成正比"

The vapor pressure of the solvent is reduced.

$$P_S = P_S^\circ x_S = P_S^\circ (1 - x_U)$$

依数性：?

The boiling point of the solvent is elevated.

$$\ln x_S = \ln(1 - x_U) = \frac{\Delta H_{vap}^\circ}{R} \left[\frac{1}{T_B} - \frac{1}{T_B^\circ} \right]$$

The freezing point of the solvent is lowered.

The solvent will display an osmotic pressure.
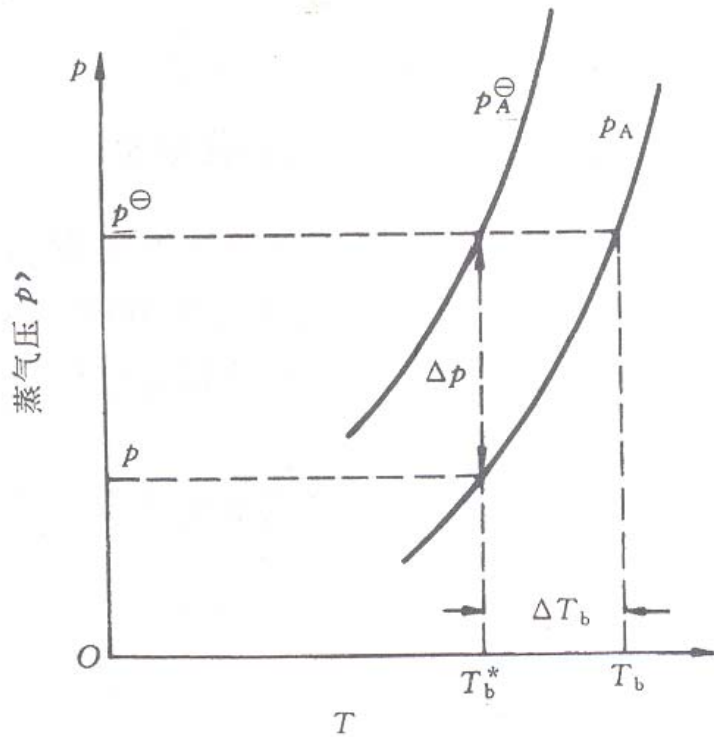
Dilute Solution and Colligative Properties (3)

图 5-6　稀溶液中溶液的沸点升高

图 5-7　稀溶液的凝固点下降

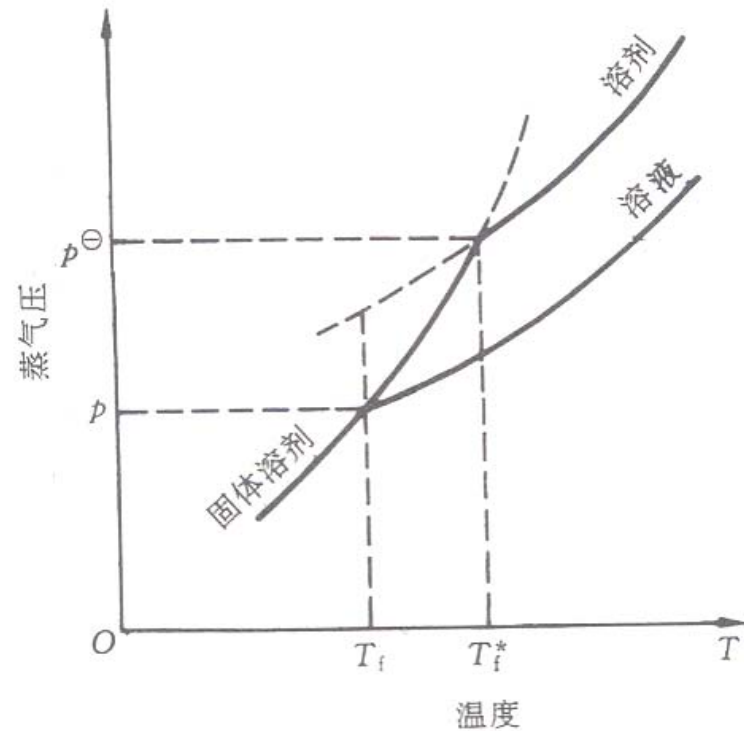# Osmotic Pressure (1)

$$\mu_A - \mu_A^\circ = RT \ln x_A \qquad \text{Raoult's law}$$

$$\mu_A - \mu_A^\circ = RT \ln(1 - x_B) = -RTx_B$$

$$\mu_A - \mu_A^\circ = \int_{P+\Pi}^{P} \underline{V}_A dP = -\underline{V}_A \Pi$$

$$\Pi = RT \frac{x_B}{\underline{V}_A}$$

半透膜！

π

Aqueous solution
(impure water)

Flexible wall

Semipermeable
membrane

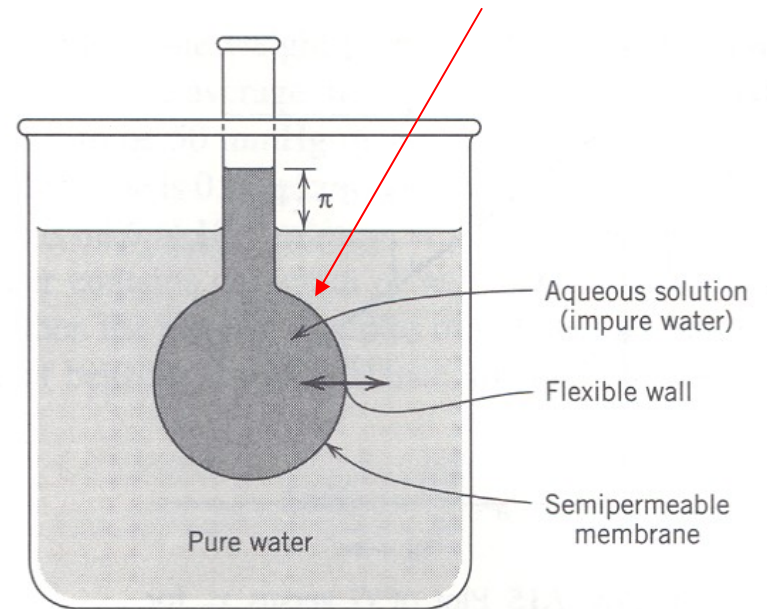Pure water

Figure 7.14 Osmotic pressure.

15:48:33

Osmotic Pressure (2)

As an example, 0.6mol/L NaCl:

$$x_B = \frac{0.6}{1000/18} = 0.0108$$

$$\Pi = \frac{2(0.0108)(8.314)(298)}{18 \times 10^{-6}} = 29.7 \times 10^5 \, N/m^2 = 29.7 atm$$

Regular Solution (1)

$$\underline{G}_M = x_A \overline{G}_A^{rel} + x_B \overline{G}_B^{rel}$$

$$\overline{G}_A^{rel} = \overline{G}_A - \underline{G}_A^\circ = RT \ln \alpha_A$$

$$\underline{G}_M = x_A RT \ln(\gamma_A x_A) + x_B RT \ln(\gamma_B x_B)$$

$$\underline{G}_M = RT(x_A \ln x_A + x_B \ln x_B) + RT(x_A \ln \gamma_A + x_B \ln \gamma_B)$$

$$\underline{G}_M = \underline{G}_M^{ideal} + \underline{G}_M^{xs}$$

$$\underline{G}_M^{ideal} = RT(x_A \ln x_A + x_B \ln x_B)$$

$$\underline{G}_M^{xs} = RT(x_A \ln \gamma_A + x_B \ln \gamma_B)$$

Regular Solution (2)

$$\ln \gamma_A = \frac{\omega}{RT} x_B^2 = \frac{\omega}{RT}(1 - x_A)^2 \qquad \underline{G}^{xs} = \underline{H}^{xs} \qquad \text{regular solution}$$

$$\underline{G}_M = RT(x_A \ln x_A + x_B \ln x_B) + RT(x_A \ln \gamma_A + x_B \ln \gamma_B)$$

$$\underline{G}_M = RT(x_A \ln x_A + x_B \ln x_B) + \underbrace{x_A \omega x_B^2 + x_B \omega x_A^2}_{\underbrace{(x_A + x_B)(\omega x_A x_B)}_{\omega x_A x_B}}$$

$$\underline{G}_M = RT(x_A \ln x_A + x_B \ln x_B) + \omega x_A x_B$$

$$\boxed{\underline{H}_M = \omega x_A x_B}$$

$$\boxed{\underline{G}_M = \underline{G}_M^{ideal} + \underline{G}_M^{xs}}$$

$$\underline{H}_M = \underline{H}_M^{ideal} + \underline{H}_M^{xs}$$

$$\underline{H}_M^{ideal} = 0$$

Regular Solution (3)

For the regular solution: $\underline{S}^{xs}_M = 0$ $\qquad \underline{G}^{xs}_M = \underline{H}^{xs}_M = \omega x_A x_B$

$$\overline{H}^{xs}_B = \underline{H}^{xs}_M + x_A \left(\frac{\partial \underline{H}^{xs}_M}{\partial x_B} \right)_T$$

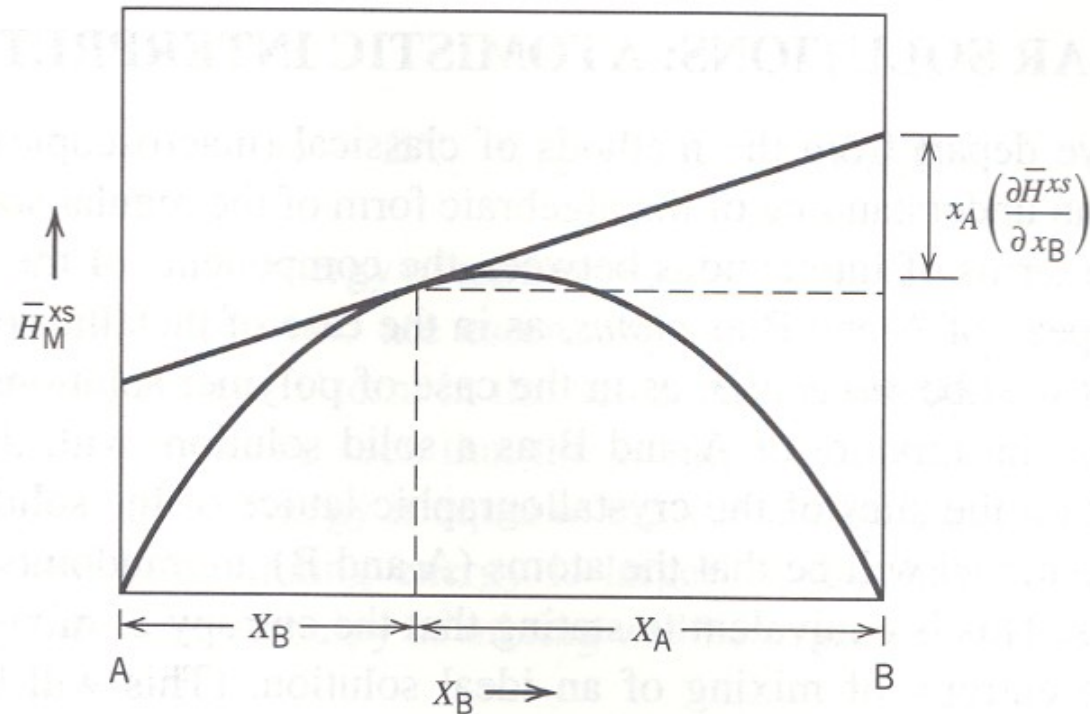**Figure 7.13** Plot of excess enthalpy of mixing versus composition for a nonideal solution.

For the regular solution: $\quad \underline{S}^{xs}{}_M = 0 \qquad \underline{G}^{xs}_M = \underline{H}^{xs}_M = \omega x_A x_B$

$$\overline{H}^{xs}_B = \underline{H}^{xs}_M + x_A \left(\frac{\partial \underline{H}^{xs}_M}{\partial x_B} \right)_T \qquad \overline{H}^{xs}_B = \omega x_A x_B + x_A \left(\frac{\partial (\omega x_A x_B)}{\partial x_B} \right)_T$$

$$\overline{H}^{xs}_B = \omega x_A x_B + x_A \omega (x_A - x_B)$$

$$\overline{H}^{xs}_B = \omega x_A^2 \qquad \overline{G}^{xs}_B = RT \ln \gamma_B \quad \Longleftarrow \quad \underline{G}^{xs}_M = RT (x_A \ln \gamma_A + x_B \ln \gamma_B)$$

$$\ln \gamma_B = \frac{\omega}{RT} x_A^2$$

Justify the algebraic form of the activity coefficient in a regular solution.

Regular Solution: Atomistic Interpretation (1)

A,B二元完全无序分布
只考虑最近邻原子间的相互作用

N_A个A原子与N_B个B原子混合形成规则溶液

Random distribution
Z: coordination number
E_{AA}: bonding energy

Table 7.1   Bond Energies After Mixing Atoms A and B in a Solid Solution

	Number of Bonds	Energy per Bond	Energy
N_{AB}	$N_A \dfrac{N_B}{N_T} Z$	E_{AB}	$\dfrac{N_A N_B}{N_T} Z E_{AB}$
N_{AA}	$\dfrac{1}{2} \dfrac{N_A^2}{N_T} Z$	E_{AA}	$\dfrac{1}{2} \dfrac{N_A^2}{N_T} Z E_{AA}$
N_{AB}	$\dfrac{1}{2} \dfrac{N_B^2}{N_T} Z$	E_{BB}	$\dfrac{1}{2} \dfrac{N_B^2}{N_T} E_{BB}$

Regular Solution: Atomistic Interpretation (2)

$$\frac{N_A Z}{2} \times \frac{N_A}{N_T}$$

$$E_M = Z\left[\frac{N_A^2}{2N_T}E_{AA} + \frac{N_B^2}{2N_T}E_{BB} + \frac{N_A N_B}{N_T}E_{AB} - \frac{N_A}{2}E_{AA} - \frac{N_B}{2}E_{BB}\right]$$

$$E_M = ZN_T\left\{\frac{[x_A^2 - x_A]E_{AA} + [x_B^2 - x_B]E_{BB}}{2}\right\} + x_A x_B E_{AB}$$

E_{AA}: bonding energy

$$\boxed{E_M = ZN_T x_A x_B\left[E_{AB} - 1/2(E_{AA} + E_{BB})\right]}$$

$\varpi = 0, \; ideal$

$\varpi \neq 0, \; \underline{S}_M^{xs} = 0, \; regular$

$$\boxed{E_M = \omega x_A x_B}$$ where $\omega = ZN_T\left[E_{AB} - 1/2(E_{AA} + E_{BB})\right]$

$$\underline{G}_M^{xs} = \underline{H}_M^{xs} - T\underline{S}_M^{xs} = \varpi x_A x_B$$

$H = U + PV = E + PV$

$\underline{S}_M^{xs} = 0$

For the regular solution: $\quad \underline{S}_M = 0 \qquad \underline{G}_M^{xs} = \underline{H}_M^{xs} = \omega x_A x_B$

$$\overline{H}_B^{xs} = \underline{H}_M^{xs} + x_A \left(\frac{\partial \underline{H}_M^{xs}}{\partial x_B} \right)_T \qquad \overline{H}_B^{xs} = \omega x_A x_B + x_A \left(\frac{\partial (\omega x_A x_B)}{\partial x_B} \right)_T$$

$$\overline{H}_B^{xs} = \omega x_A x_B + x_A \omega (x_A - x_B)$$

$$\overline{H}_B^{xs} = \omega x_A^2 \qquad \overline{G}_B^{xs} = RT \ln \gamma_B$$

$$\ln \gamma_B = \frac{\omega}{RT} x_A^2$$

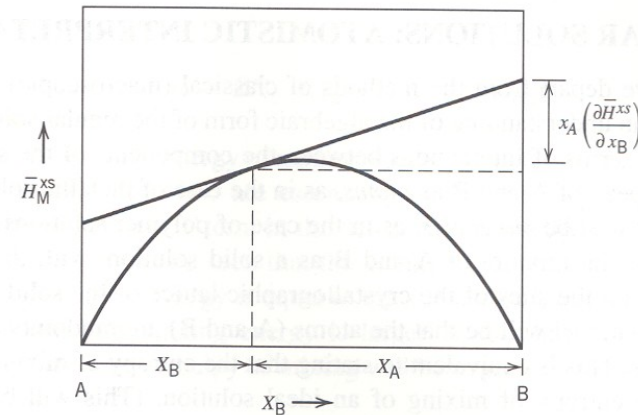Justify the algebraic form of
in a regular solution.

Figure 7.13 Plot of excess enthalpy of mixing versus composition for a nonideal solution.

Non-ideal Solution
Gibbs-Duhem Relation
Dilute Solution and Colligative Properties

Non-ideal Solution: 非理想溶液
Activity coefficient: 活度系数
Gibbs-Duhem Relation：Gibbs-Duhem关系式
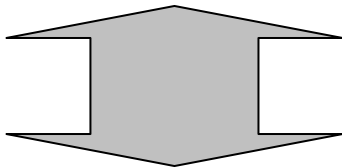Dilute Solution：稀溶液
Colligative Properties：依数性
Osmotic Pressure：渗透压

规则溶液

- ## 非理想溶液

$$\ln \gamma_A = \frac{\omega}{RT} x_B^2 = \frac{\omega}{RT} \left(1 - x_A\right)^2$$

$$\underline{S}^{xs}{}_M = 0$$

$$\underline{G}^{xs}_M = \underline{H}^{xs}_M = \omega x_A x_B$$

Homework

- Exercises in Chap 6

  P 195, 7.5, 7.7