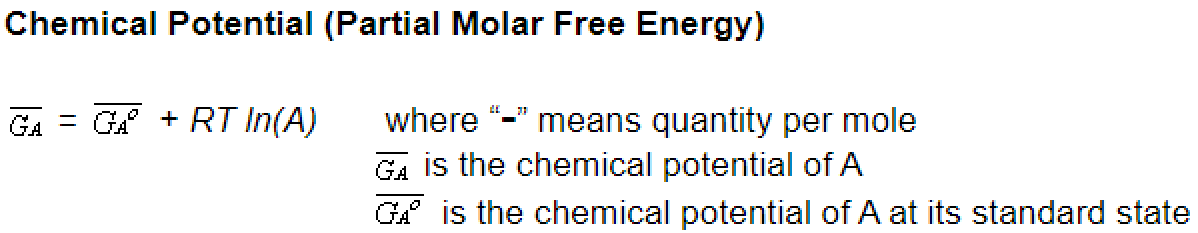
Thermodynamics of Transport System

-Dr. Ekta Khare
Department of Microbiology
Institute of Biosciences & Biotechnology,
CSJM University, Kanpur

Thermodynamics of Passive Transport (Passive diffusion)

- When two aqueous compartments containing unequal concentrations of a soluble compound are separated by a permeable divider (membrane), the solute moves by **simple diffusion from the region of higher** concentration, through the membrane, to the region of lower concentration, until the two compartments have equal solute concentrations.
- **For molecule A neutral in Charge:**

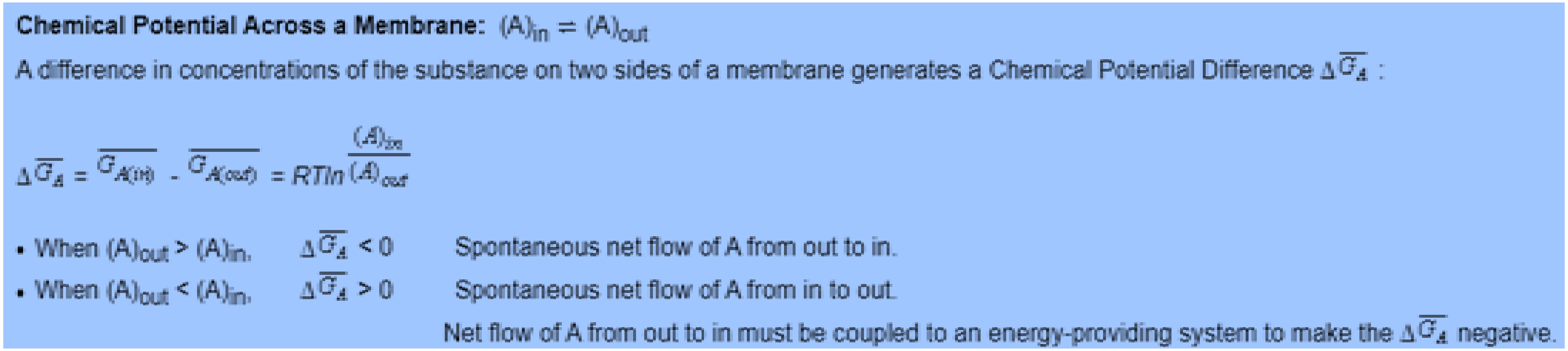


Chemical Potential (Partial Molar Free Energy)

$\overline{G_A} = \overline{G_A^o} + RT\ ln(A)$ where "**-**" means quantity per mole

$\overline{G_A}$ is the chemical potential of A

$\overline{G_A^o}$ is the chemical potential of A at its standard state



Chemical Potential Across a Membrane: $(A)_{in} = (A)_{out}$

A difference in concentrations of the substance on two sides of a membrane generates a Chemical Potential Difference $\Delta\overline{G_A}$:

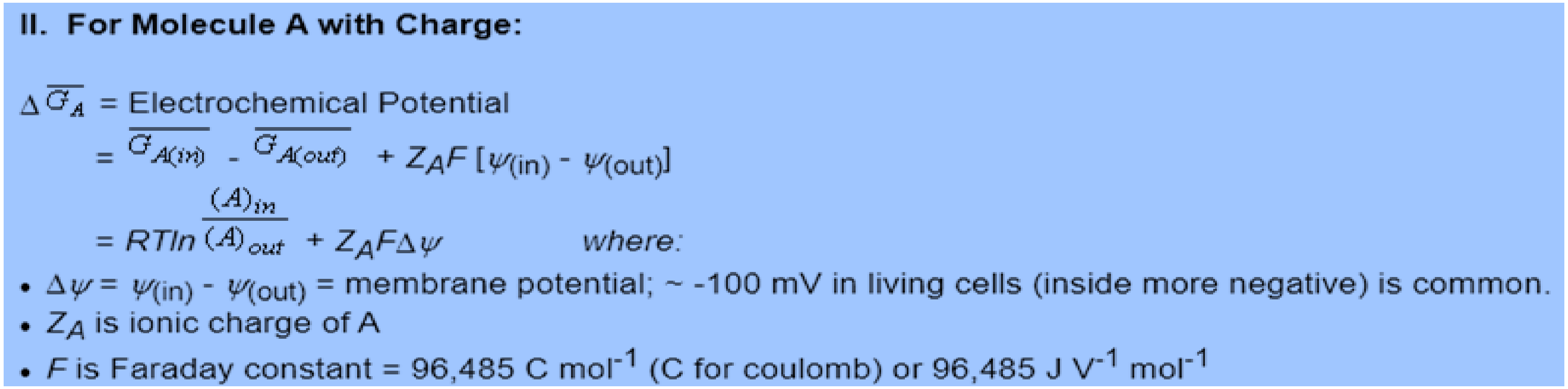
$$\Delta\overline{G_A} = \overline{G_{A(in)}} - \overline{G_{A(out)}} = RTln\frac{(A)_{in}}{(A)_{out}}$$

- When $(A)_{out} > (A)_{in}$, $\Delta\overline{G_A} < 0$ Spontaneous net flow of A from out to in.
- When $(A)_{out} < (A)_{in}$, $\Delta\overline{G_A} > 0$ Spontaneous net flow of A from in to out.

Net flow of A from out to in must be coupled to an energy-providing system to make the $\Delta\overline{G_A}$ negative.

Thermodynamics of Facilitated Diffusion

- When ions of opposite charge are separated by a permeable membrane, there is a transmembrane electrical gradient, a **membrane potential, ψ (expressed in Vm).**
- This membrane potential produces a force opposing ion movements that increase *Vm* and *driving ion* movements that reduce *Vm.*
- Thus the direction in which a charged solute tends to move spontaneously across a membrane depends on both the chemical gradient (the difference in solute concentration) and the electrical gradient (*Vm*) across the membrane.
- Together, these two factors (chemical and electrical gradient) are referred to as the **electrochemical gradient or electrochemical potential.**



II. For Molecule A with Charge:

$\Delta\overline{G_A}$ = Electrochemical Potential

$$= \overline{G_{A(in)}} - \overline{G_{A(out)}} + Z_A F\,[\psi_{(in)} - \psi_{(out)}]$$

$$= RT\ln\frac{(A)_{in}}{(A)_{out}} + Z_A F \Delta\psi \qquad \textit{where:}$$

- $\Delta\psi = \psi_{(in)} - \psi_{(out)}$ = membrane potential; ~ -100 mV in living cells (inside more negative) is common.
- Z_A is ionic charge of A
- F is Faraday constant = 96,485 C mol^{-1} (C for coulomb) or 96,485 J V^{-1} mol^{-1}

- This behavior of solutes is in accord with the second law of thermodynamics: molecules tend to spontaneously assume the distribution of greatest randomness and lowest energy.

... **Thermodynamics of Facilitated Diffusion**

- To pass through a lipid bilayer, a polar or charged solute must first give up its interactions with the water molecules in its hydration shell, then diffuse about 3 nm (30 Å) through a solvent (lipid) in which it is poorly soluble.
- The energy used to strip away the hydration shell and to move the polar compound from water into and through lipid is regained as the compound leaves the membrane on the other side and is rehydrated.
- However, the intermediate stage of transmembrane passage is a high-energy state comparable to the transition state in an enzyme-catalyzed chemical reaction.
- In both cases, an activation barrier must be overcome to reach the intermediate stage.
- The energy of activation ($G^{\ddagger}$) *for* translocation of a polar solute across the bilayer is so large that pure lipid bilayers are virtually impermeable to polar and charged species over periods of time relevant to cell growth and division.

... **Thermodynamics of Facilitated Diffusion**

- Membrane proteins lower the activation energy for transport of polar compounds and ions by providing an alternative path through the bilayer for specific solutes.
- Proteins that bring about this **facilitated diffusion, or passive transport, are not enzymes in the usual sense;** their “substrates” are moved from one compartment to another, but are not chemically altered.
- Membrane proteins that speed the movement of a solute across a membrane by facilitating diffusion are called **transporters** or **permeases.**

... **Thermodynamics of Facilitated Diffusion**

- Like enzymes, transporters bind their substrates with stereochemical specificity through multiple weak, noncovalent interactions.
- The negative free-energy change associated with these weak interactions, $G_{binding}$, counterbalances the positive free-energy change that accompanies loss of the water of hydration from the substrate, $G_{dehydration}$, *there by lowering* $G^{\ddagger}$ for transmembrane passage.
- Transporters span the lipid bilayer several times, forming a transmembrane channel lined with hydrophilic amino acid side chains.
- The channel provides an alternative path for a specific substrate to move across the lipid bilayer without its having to dissolve in the bilayer, further lowering $G^{\ddagger}$ for transmembrane diffusion.
- The result is an increase of several orders of magnitude in the rate of transmembrane passage of the substrate.

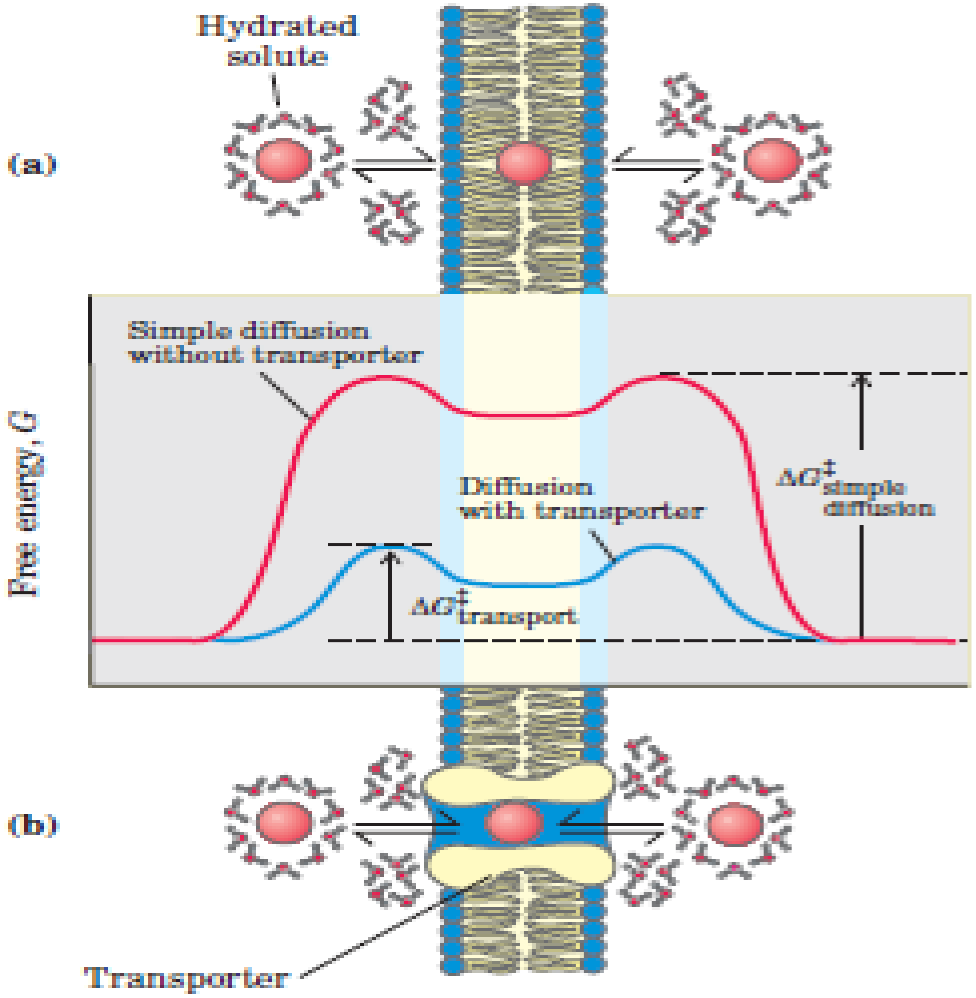


FIGURE 11–28 Energy changes accompanying passage of a hydrophilic solute through the lipid bilayer of a biological membrane. (a) In simple diffusion, removal of the hydration shell is highly endergonic, and the energy of activation ($\Delta G^{\ddagger}$) for diffusion through the bilayer is very high. **(b)** A transporter protein reduces the $\Delta G^{\ddagger}$ for transmembrane diffusion of the solute. It does this by forming noncovalent interactions with the dehydrated solute to replace the hydrogen bonding with water and by providing a hydrophilic transmembrane passageway.

Thermodynamics of Active transport

- Active transport is thermodynamically unfavorable (endergonic).

$$\Delta \bar{G}_A = \bar{G}_A(in) - \bar{G}_A(out) = RT in \left(\frac{[A]_{in}}{[A]_{out}}\right)$$

- If [A] is greater inside than outside, ΔG_A is positive and an inward net flow of A can occur only if an exergonic process, such as ATP hydropysis, is coupled to it to make the overall free energy change negative.
- The amount of energy needed for the transport of a solute against a gradient can be calculated from the initial concentration gradient.

… Thermodynamics of Active transport

- The transport of a solute from a region where its concentration is C1 to a region where its concentration is C2, no bonds are made or broken and the standard free-energy change, G, is zero.
- The free-energy change for transport, G_t, is then

$$\Delta G_t = RT \ln \frac{C_2}{C_1} \tag{1}$$

- If there is a tenfold difference in concentration between two compartments, the cost of moving 1 mol of an uncharged solute at 25° C across a membrane separating the compartments is therefore

$$\begin{aligned}\Delta G_t &= (8.315\ \mathrm{J/mol \cdot K})(298\ \mathrm{K})(\ln 10/1) = 5{,}700\ \mathrm{J/mol} \\ &= 5.7\ \mathrm{kJ/mol}\end{aligned}$$

- **Equation 1 holds for all uncharged solutes.**

... **Thermodynamics of Active transport**

- When the solute is an ion, its movement without an accompanying counterion results in the endergonic separation of positive and negative charges, producing an electrical potential; such a transport process is said to be electrogenic.
- **The energetic cost of moving an ion** depends on the electrochemical potential, the sum of the chemical and electrical gradients:

$$\Delta G_t = RT \ln\left(\frac{C_2}{C_1}\right) + Z\mathcal{F}\Delta\psi \qquad \textbf{(2)}$$

- Inward transport of an ionic molecule is an endergonic process that, in most cases, is coupled to the hydrolysis of ATP.
- In case of co-transport, the energy made available by the spontaneous flow of protons across a membrane is calculable from Equation 2;.
- Remember that G for flow down an electrochemical gradient has a negative value, and *G for transport of ions against* an electrochemical gradient has a positive value.

Thermodynamics of Group Translocation

- This is a type of energy-dependent transport because metabolic energy is used.
- The best-known group translocation system is the phosphoenolpyruvate: sugar phosphotransferase system (PTS).

PEP + sugar (outside) → pyruvate + sugar-P (inside)

- The negative **free energy** change comes instead from the fact that the bonds formed after hydrolysis for example in phosphotransferse system - are lower in **energy** than the bonds present before hydrolysis, drives the inward transport of molecule during group translocation.

Questions

- Write an essay on thermodynamics of transport system.
- Explain how bacterial transport system follows second law of thermodynamics?
- Write note on thermodynamics of:
    - Passive Transport
    - Active transport
    - Facilitated diffusion
    - Group translocation