

Thermodynamics of Biological Systems – Chapter 3

- Thermodynamics

- Heat Movement

- What processes require energy?
- Where does the energy to do the above processes come from?

Why is knowledge of thermodynamics important?

- To study the bioenergetics of life
- To determine whether chemical processes occur spontaneously

Basic concepts of Thermodynamics

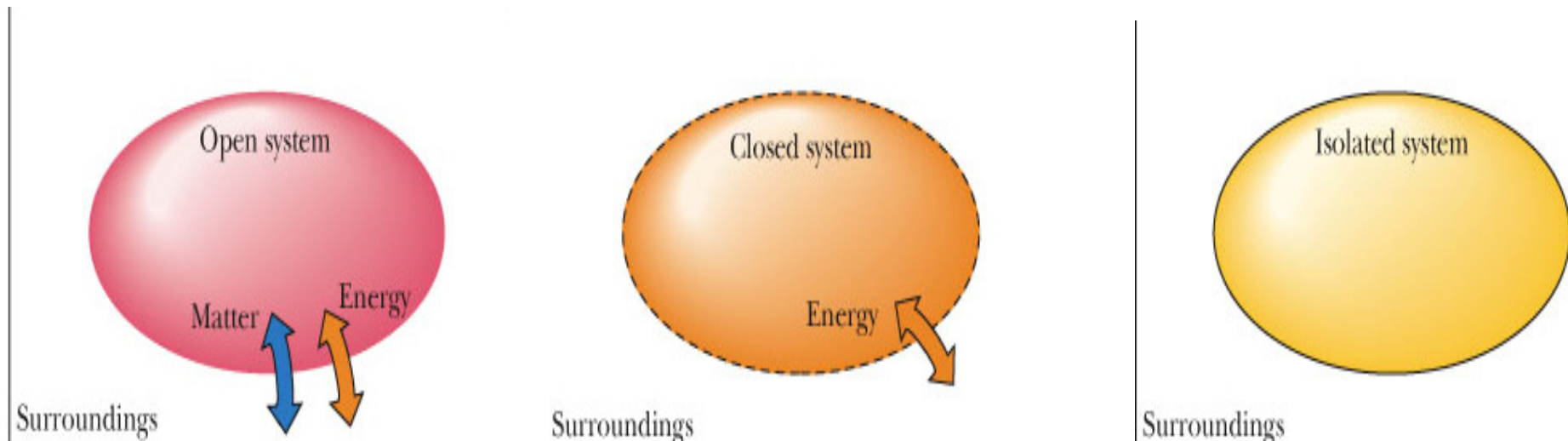
System

The portion of the universe that we are interested in

Surroundings

Everything else

Isolated, closed or open system



The first law of Thermodynamics

- Heat can be converted to other forms of energy
- **Internal energy (E)** represents all energies exchanged in physical or chemical reactions

The first law of Thermodynamics

- Internal energy is independent of path
- Therefore E is a **STATE FUNCTION**

A state function is a parameter that depends only on the present state of the system and not on how the system reached that state

- How can E be changed?

The first law of Thermodynamics

$$\Delta E = E_2 - E_1 = q + w$$

The **change in internal energy** for the process of converting one state into another

Heat absorbed by the system from the surroundings **Work** done on the system by the surroundings

$$w = -P\Delta V$$

For chemical systems where pressure and volume of the system is a concern. This is when work is done on the system and the sign is positive

Mechanical Work:

Movement through some distance through the application of a force

Enthalpy

$$\Delta E = E_2 - E_1 = q + w \quad \& \quad w = -P\Delta V$$

- **Pressure** in biological systems is normally constant so define a new function (enthalpy) that deals with constant pressure $H = E + PV$

$$\Delta H = \Delta E + P\Delta V = q + w + P\Delta V = q - P\Delta V + P\Delta V = q$$

- What is the change in volume in a typical cell (biological systems)?
- $\therefore w = -P(0)$ and $\Delta E = q$

- Thermodynamic parameters are generally compared for different reactions

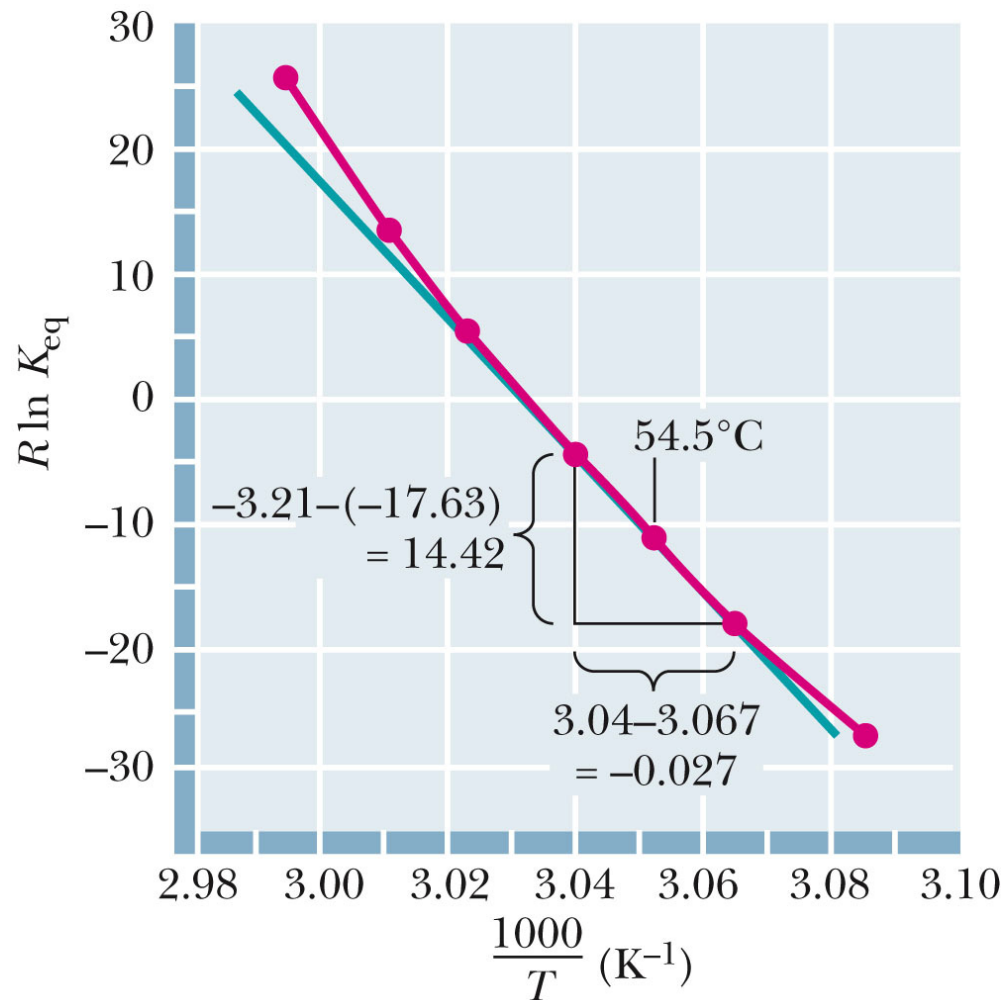
For solutes in solution, the standard state “o” is normally unit activity (1 M concentration)

- How can we measure ΔH ?

$$\Delta H^\circ = -R \frac{d(\ln K_{eq})}{d\frac{1}{T}}$$

- True for any reaction $A \leftrightarrow B$ at equilibrium

Gas constant: $8.315 \text{ J. mol}^{-1} \cdot \text{K}^{-1}$



van't Hoff plot

Temperature-induced unfolding
of chymotrypsinogen

This indicates H-bond breaking and exposure
of buried hydrophobic groups

The Second Law of Thermodynamics

- Entropy (S): a measure of the disorder and randomness in a system

Boltzmann's constant:

$1.38 \times 10^{-23} \text{ J/K}$


$$\Delta S = k \ln W_{\text{final}} - k \ln W_{\text{initial}}$$

- W = number of microstates

The Third Law of Thermodynamics

The entropy of any crystalline, perfectly ordered substance must approach 0 as the absolute temperature approaches 0 K

$$S = \int_0^T C_p d \ln T$$

↓
Absolute
entropy

↓
Heat
capacity at
constant
pressure

$$C_P = \frac{dH}{dT}$$

C_p is the amount of heat 1 mol of a substance can store when its temperature is raised by 1 degree

- $\Delta C_p > 0$ implies molecules have acquired **new ways to move** in a process and thus have new ways to store heat energy
- $\Delta C_p < 0$ implies the process has resulted in **less freedom of motion** for the molecules involved

Free Energy and Equilibrium

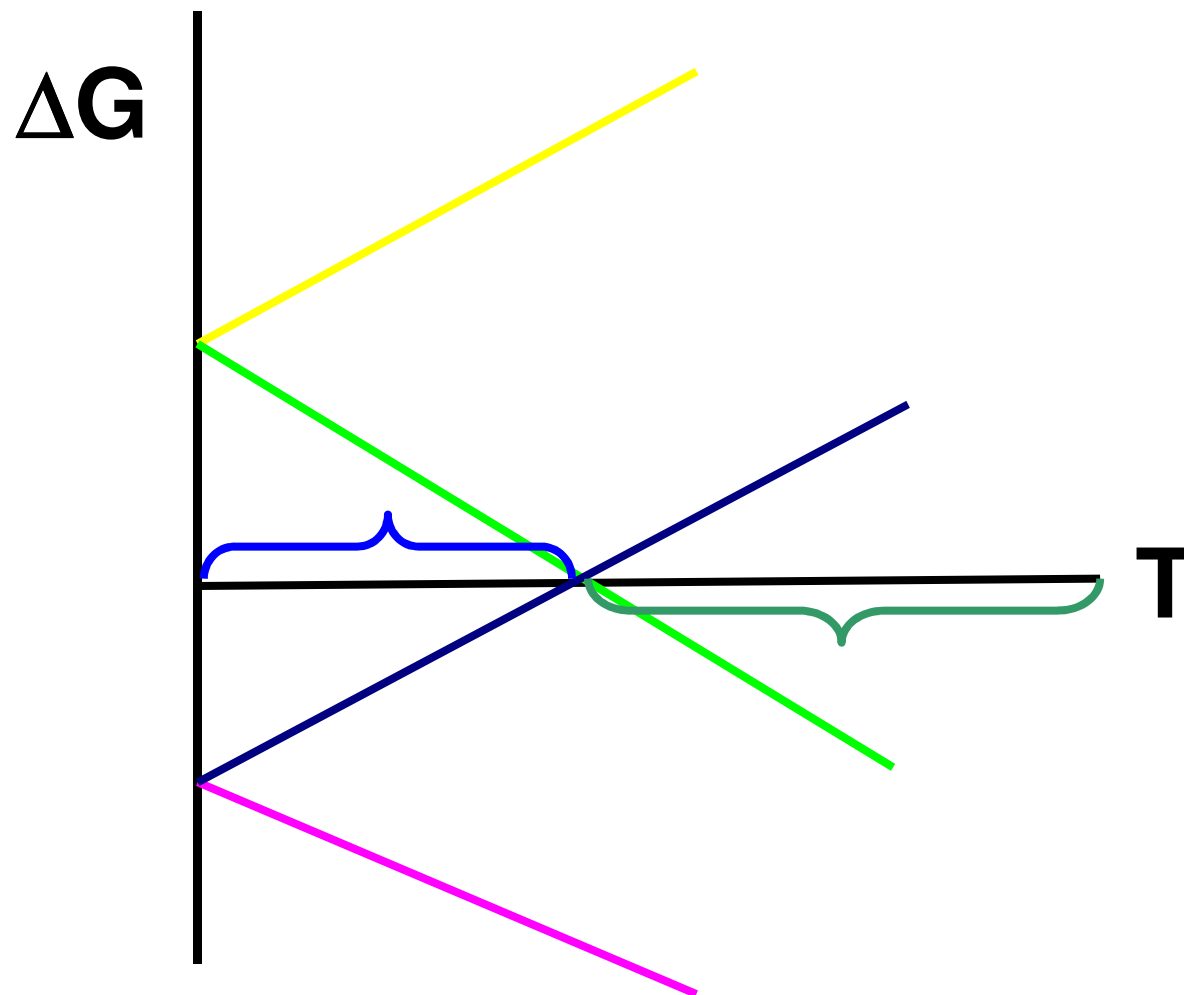
- Will the reaction proceed in the direction written?

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

- If $\Delta G = 0$?
- If $\Delta G \neq 0$?

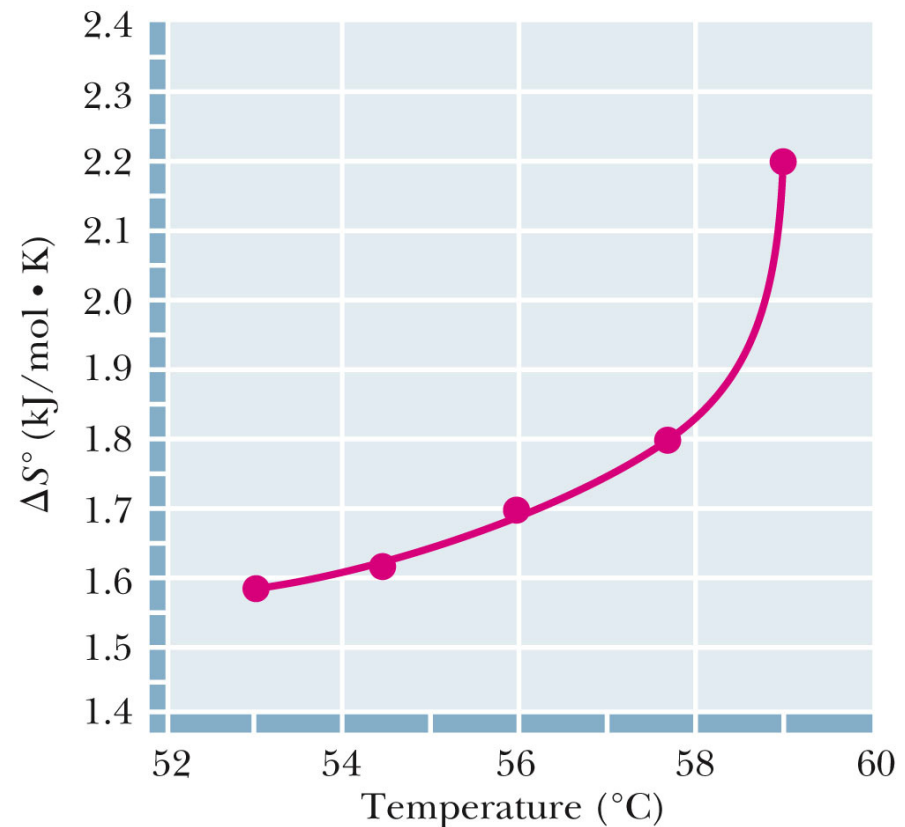
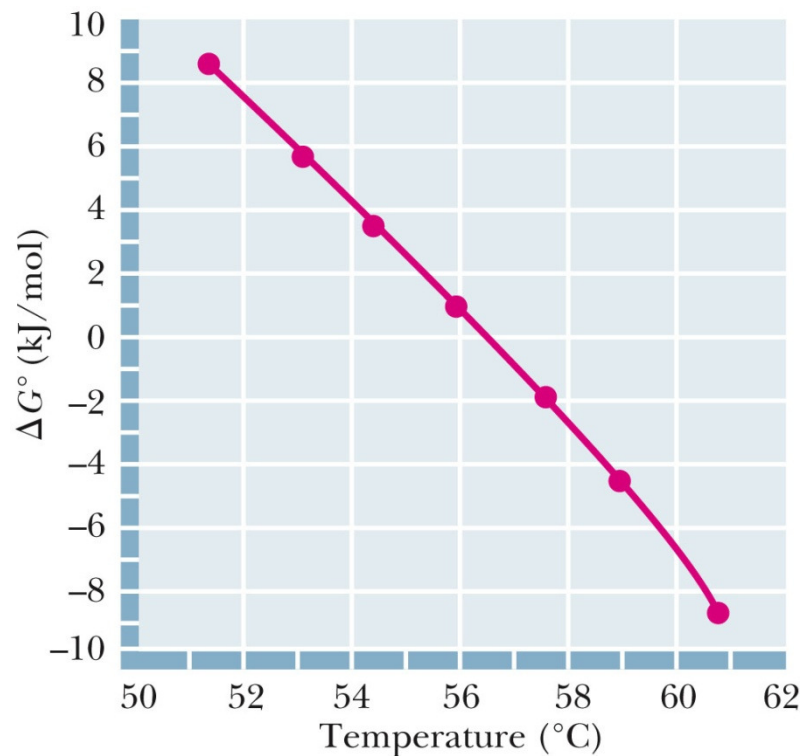
- If $\Delta G < 0$?
- If $\Delta G > 0$?

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



Dependence of ΔG° and ΔS° on temperature

Unfolding of chymotrypsinogen



Standard state free energy change

For $A + B \leftrightarrow C + D$

Free energy for non-standard state conditions:

$$\Delta G = \Delta G^\circ + RT \ln ([C][D]/[A][B])$$

$$\Delta G^\circ = -RT \ln (K_{eq})$$

Point of equilibrium for a reaction in solution is a function of ΔG° for that process

So standard state (1M) free energy changes can be determined if the K_{eq} is known

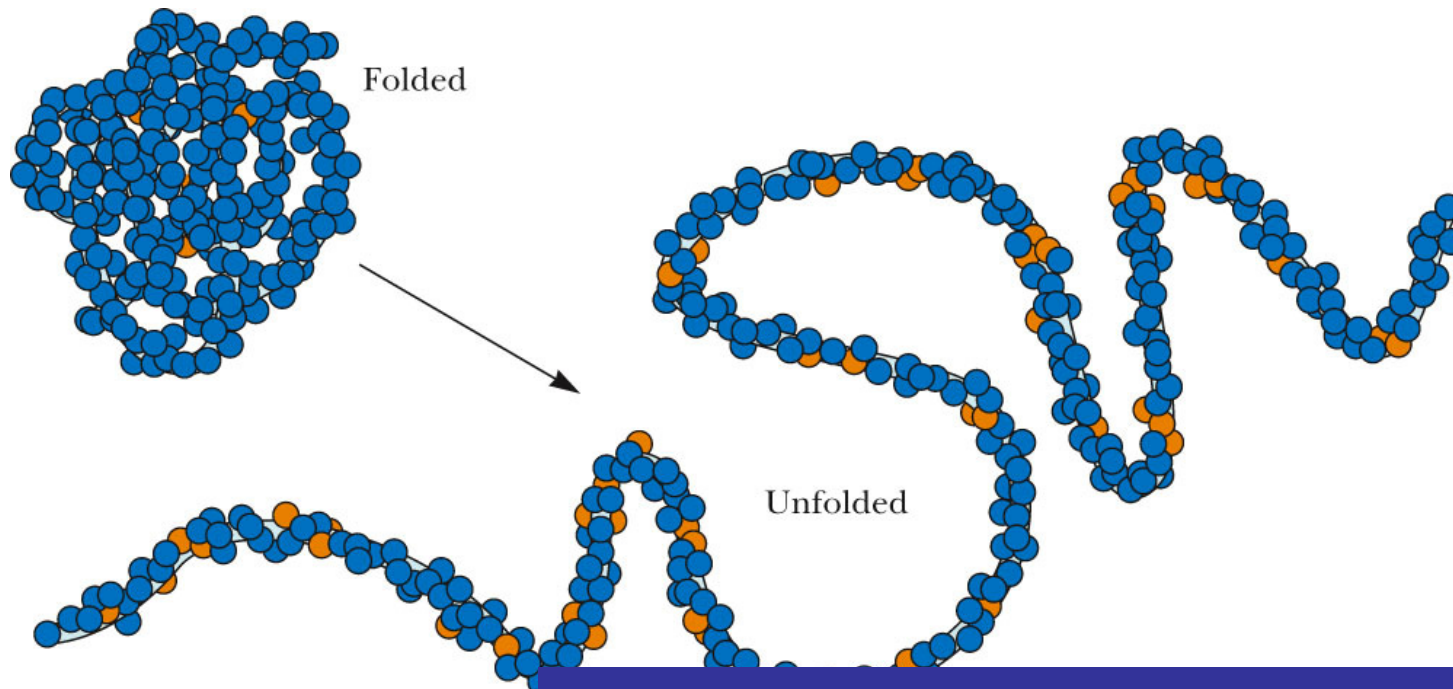
The effect of pH on standard state free energy

- Standard state for H^+ is 1M which corresponds to $pH = 0$
- In biological systems we should deal with free energies at $pH\ 7$
- Modified standard state (‘) **Eg $\Delta G^{\circ'}$ $\Delta H^{\circ'}$ etc**

10^{-7} M H^+ and unit activity (1M for solutions, 1atm for gasses)

What can thermodynamic parameters tell us about biochemical events?

- ΔH ? **Single value not so useful but a comparison of several parameters gives meaningful insights**



Protein unfolding, ΔG , ΔH ΔS ?

Analysis of processes according to thermodynamics

| TABLE 3.2 Thermodynamic Parameters for Several Simple Processes* | | | | |
|---|----------------------------|--------------------------------|----------------------------|----------------------------|
| Process | ΔH° kJ/mol | ΔS° kJ/mol · K | ΔG° kJ/mol | ΔC_p kJ/mol · K |
| Hydration of ions [†] | | | | |
| $\text{Na}^+(\text{g}) + \text{Cl}^-(\text{g}) \longrightarrow \text{Na}^+(\text{aq}) + \text{Cl}^-(\text{aq})$ | -760.0 | -0.185 | -705.0 | |
| Dissociation of ions in solution [†] | | | | |
| $\text{H}_2\text{O} + \text{CH}_3\text{COOH} \longrightarrow \text{H}_3\text{O}^+ + \text{CH}_3\text{COO}^-$ | -10.3 | -0.126 | 27.26 | -0.143 |
| Transfer of hydrocarbon from pure liquid to water [†] | | | | |
| Toluene (in pure toluene) \longrightarrow toluene (aqueous) | 1.72 | -0.071 | 22.7 | 0.265 |

Labile vs non labile waters



Freedom to exchange H-bonds

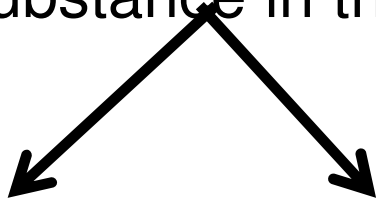
High Energy Biomolecules

- Release of chemical energy →

Controlled exergonic reactions **that drive life**

Mediated by high energy molecules

High energy molecules: React spontaneously with a substance in the environment ($\Delta G^{\circ'} < -25 \text{ kJ/mol}$)



High energy phosphate compounds and thioester

TABLE 3.3 Free Energies of Hydrolysis of Some High-Energy Compounds*

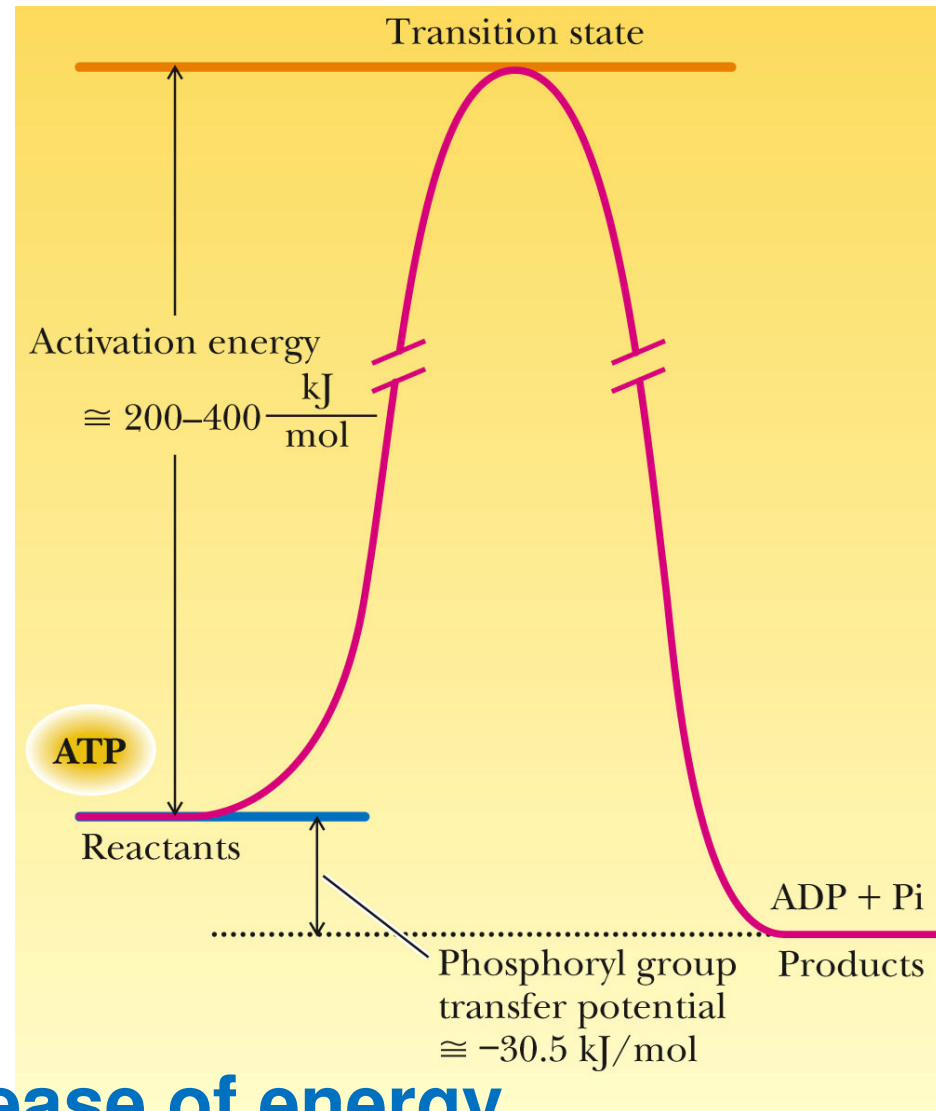
| Compound and Hydrolysis Reaction | $\Delta G'^{\circ}$ (kJ/mol) | Structure |
|---|------------------------------|--------------|
| Phosphoenolpyruvate \longrightarrow pyruvate + P_i | -62.2 | Figure 3.13 |
| 1,3-Bisphosphoglycerate \longrightarrow 3-phosphoglycerate + P_i | -49.6 | Figure 3.12 |
| Creatine phosphate \longrightarrow creatine + P_i | -43.3 | Figure 13.21 |
| Acetyl phosphate \longrightarrow acetate + P_i | -43.3 | Figure 3.12 |
| Adenosine-5'-triphosphate \longrightarrow ADP + P_i | -35.7 [†] | Figure 3.9 |
| Adenosine-5'-triphosphate \longrightarrow ADP + P_i (with excess Mg^{2+}) | -30.5 | Figure 3.9 |
| Adenosine-5'-diphosphate \longrightarrow AMP + P_i | -35.7 | Figure 3.11 |
| Pyrophosphate \longrightarrow P_i + P_i (in 5 mM Mg^{2+}) | -33.6 | Figure 3.10 |
| Adenosine-5'-triphosphate \longrightarrow AMP + PP_i (excess Mg^{2+}) | -32.3 | Figure 10.11 |
| Uridine diphosphoglucose \longrightarrow UDP + glucose | -31.9 | Figure 22.10 |
| Acetyl-coenzyme A \longrightarrow acetate + CoA | -31.5 | page 570 |
| S-adenosylmethionine \longrightarrow methionine + adenosine | -25.6 [‡] | Figure 25.28 |
| Glucose-1-phosphate \longrightarrow glucose + P_i | -21.0 | Figure 7.13 |
| <i>Sn</i> -Glycerol-3-phosphate \longrightarrow glycerol + P_i | -9.2 | Figure 8.5 |
| Adenosine-5'-monophosphate \longrightarrow adenosine + P_i | -9.2 | Figure 10.11 |

Properties of High Energy Molecules

- Not long term energy storage substances
- These molecules are not particularly unstable and the term “high energy compound” must not be confused with a high energy state

Enzymes required

Energy barrier to hydrolysis of ATP far higher than the energy difference between ATP and ADP + P



Net release of energy