# Catalysis

## 1. Background

**a) Motivation for Catalysis** -- The reaction $A \rightleftarrows B$ is slow because of a large $E_a$. How do we accelerate product formation ? Raise the reaction temperature ? This is a possible solution, but suppose the reaction is exothermic ($\Delta H < 0$). Then,

$$\frac{d \ln K_{eq}}{dT} = \frac{\Delta H^0}{RT^2}; \quad K_{eq} = \frac{[B]}{[A]} \quad \text{decreases with T!}$$

Thus, the yield of product goes down as the rate increases ! How do we maintain the yield and concurrently increase the rate ? Often it is possible to find a **catalyst** which will accomplish this goal. For example, instead of

$$A \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} B$$

we utilize

$$A + C \underset{k_{-2}}{\overset{k_2}{\rightleftarrows}} B + C$$

Where $k_2 > k_1$ because of the catalyst C. In general the catalyst, is not destroyed by the reaction.

**b) Effectiveness of Catalyst** -- Catalyst can be very effective at accelerating reaction rates. Consider the reaction

$$H_2O_2 \xrightarrow{\text{Catalase}} H_2O + \tfrac{1}{2}O_2$$

| Catalyst | Velocity ($-d[H_2O_2]/dt$) (M/sec) | $E_a$ (kJ/mole) |
|---|---|---|
| None | $10^{-8}$ | 71 |
| HBr | $10^{-4}$ | 50 |
| $Fe^{2+}/Fe^{3+}$ | $10^{-3}$ | 42 |
| Catalase (enzyme) | $10^{7}$ | 8 |

Reaction velocity accelerates by a **factor of $10^{15}$ ! ! !**

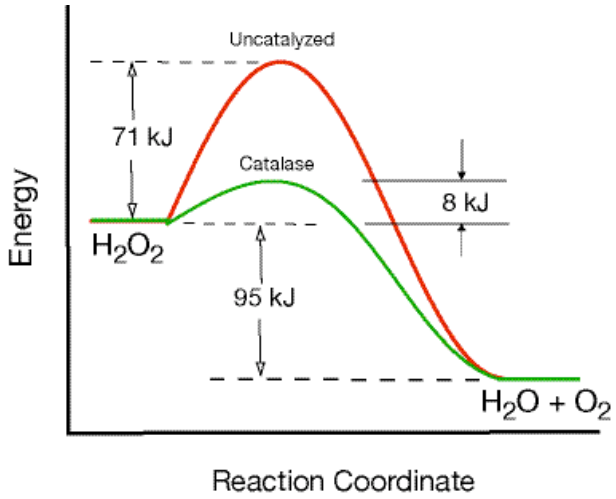
$$(NH_2)C{=}O + H_2O \xrightarrow{\text{Urease}} CO_2 + NH_2$$

| Catalyst | -d[Urea]/dt | $E_a$ (kJ/mole) |
|---|---|---|
| None | No reaction | • |
| $H_3O^+$ | $10^{-8}$ | 100 |
| Urease | $10^7$ | 7 |

Again, an acceleration of $\mathbf{10^{15}}$ !

As illustrated above **enzymes** are very effective catalysts. Sometimes they are very specific -- ie, a small change in the substrate will disable their function. Others react with large classes of molecules -- phosphatase cleaves a large number of different phosphate esters.

**2) Function of a Catalyst** -- a catalyst lowers $E_a$ and therefore accelerates the reaction. Often the mechanism of the reaction is also altered.




In the case above $E_a$ is lowered from 71 to 8 kJ/mole, However, for the reaction

$$A + C \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} B + C$$

the equilibrium constant is

$$K_{eq} = \frac{k_2}{k_{-2}} = \frac{[B][C]}{[A][C]} = \frac{[B]}{[A]}$$

Thus, the position of the equilibrium is not altered by the presence of *C* !

**3) Types of Catalysts** -- Catalyst and catalytic processes are divided into two categories:

**a) Homogeneous catalyst** occupies the same phase as the reactants: thus,

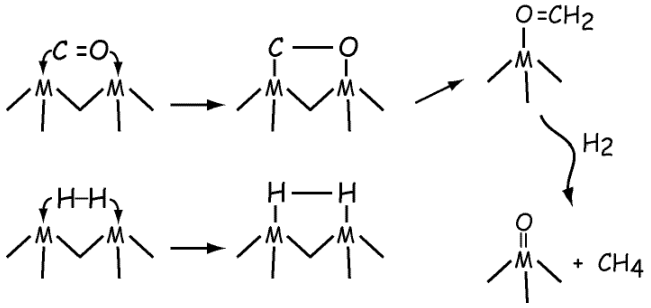
$$H_2O_2 \xrightarrow{\text{Catalase}} H_2O + \tfrac{1}{2}O_2$$

$$CH_3\text{-}\overset{O}{\overset{\|}{C}}\text{-}OEt + H_2O \xrightarrow{H^+} CH_3COOH + EtOH$$

**b) Heterogeneous Catalyst** is in a different phase than the reactants: for example a liquid (reactants)-solid (catalyst) or gas (reactants)-solid (catalyst)

$$3H_2 + CO \xrightarrow{Ni/Al_2O_3} CH_4 + H_2O$$

$\Delta G^\circ$ (500 K) = -94.4 kJ/mole, $K_{eq}$ ~ 1.2 x $10^{10}$ but in the absence of a catalyst, the rate is very slow.




How does the catalyst function -- mechanism of $3H_2$ + CO on Ni.

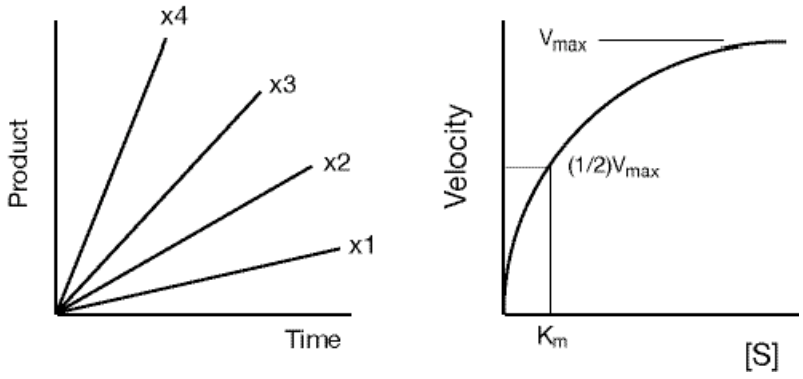
Thus, heterogeneous or surface catalysis involves adsorption of reactants on active sites.

Sometimes the distinction between homogeneous and heterogeneous catalysis is not clear. For example, many membrane bound enzymes are involved in catalysis. Is this hetero- or homogenous catalysis?

**4). Enzyme Catalysis**

**a) Michaelis-Menten Equation**

Enzymes are large molecules ($m_w$ = $10^4$-$10^6$) which catalyze biochemical reactions. Typically, they are ~ 10-100 nm diameter and are sometimes immobilized in membranes. Two typical experimental observations are




(a) Product formation is linear in [E]
(b) For fixed [E], velocity a [S] and rate approaches a maximum or saturating velocity.
(c) We will consider the initial rate regime.

Consider the general reaction

$$E + S \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} ES \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} E + P$$

In most experimental circumstances

$$[E] \ll [S] \text{ and } [ES] \ll [S]$$

therefore, steady state approximation is valid.

$$d[ES]/dt = k_1 [E] [S] - k_{-1} [ES] - k_2 [ES] + k_{-2} [E] [P] = 0$$

We often do not know [E], but we do know

$$[E]_0 = [E] + [ES] \quad \& \quad [E] = [E]_0 - [ES]$$

$$([E]_0 - [ES]) \quad [\ k_1[S] + k_{-2}[P]\ ] - (k_{-1} + k_2)[ES] = 0$$

$$[ES](k_{-1} + k_2 + k_1[S] + k_{-2}[P]) = [E]_0(k_1[S] + k_{-2}[P])$$

$$[ES] = \frac{k_1[S] + k_{-2}[P]}{k_{-1} + k_2 + k_1[S] + k_{-2}[P]}[E]_0$$

The reaction rate is - d[S]/dt, which yields

$$V \equiv \frac{-d[S]}{dt} = k_1[E][S] - k_{-1}[ES]$$

$$= k_1([E]_0 - [ES])[S] - k_{-1}[ES]$$

$$V = k_1[E]_0[S] - (k_1[S] + k_{-1})[ES]$$

Since $[ES] \simeq 0$,

$$-\frac{d[S]}{dt} = \frac{d[P]}{dt}$$

$$V = k_1[E]_0[S] - (k_1[S] + k_{-1}) \left[\frac{k_1[S] + k_{-2}[P]}{k_{-1} + k_2 + k_1[S] + k_{-2}[P]}[E]_0\right]$$

which yields

$$V = \frac{k_1k_2[S] - k_{-1}k_{-2}[P]}{k_{-1} + k_2 + k_1[S] + k_{-2}[P]}[E]_0$$

In the initial rate regime $[P] \simeq 0$ (and $[S] \simeq [S]_0$)

**Michaelis-Menton Equation:**

$$V = \frac{k_2[S]}{[S] + \frac{k_{-1} + k_2}{k_1}}[E]_0 = \frac{k_2[S]}{[S] + K_m}[E]_0$$

where

$$K_m = \frac{k_{-1} + k_2}{k_1} \qquad \text{Michaelis Constant}$$

Some limiting cases of importance:

$[S] >> K_m \qquad V = k_2[E]_0 = V_{max}$

$[S] << K_m \qquad V = \frac{V_{max}}{K_m}[S]$

$[S] \sim K_m \qquad V = \frac{V_{max}}{2}$

The Michaelis Constant, $K_m$, equals [S] that yields half the maximum velocity! Small $K_m$ means that the enzyme binds the substrate tightly, and small [S]'s are sufficient to saturate the enzyme and to approach maximum catalytic efficiency.

**b) Lineweaver-Burke Analysis**

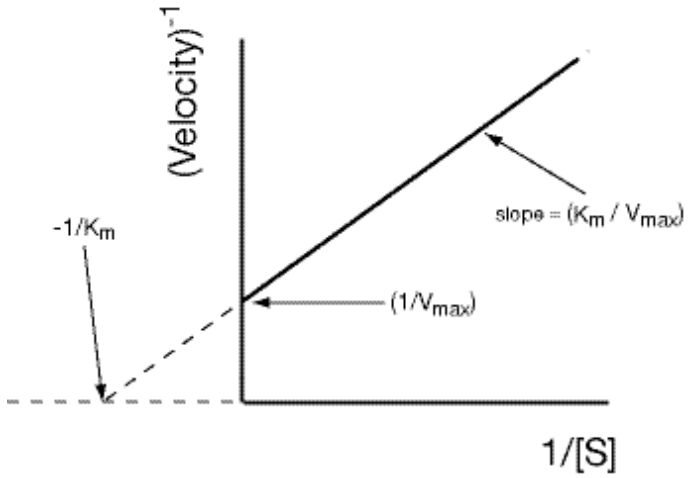
Rewriting V in terms of $V_{max}$, we obtain

$$V = \frac{V_{max}[S]}{K_m + [S]}$$

**Lineweaver-Burke Equation:**

$$\boxed{\frac{1}{V} = \frac{K_m}{V_{max}[S]} + \frac{1}{V_{max}}}$$

which leads to a **Lineweaver-Burke Plot**




$$Turnover\ Number = \frac{Number\ moles\ product}{Number\ moles\ binding\ site \bullet sec}$$

$$= \frac{V_{max}}{[E_0]} = k_2$$

**c) Comments about Michaelis-Menton:**

(a) $M^2$ is an oversimplification. In many situations EP and other ES complexes exist.

(b) $M^2$ was developed when enzyme's were rare and difficult to obtain. With genetic engineering, E's are readily available and kinetic analysis will change.

# Relaxation Kinetics

(M. Eigen-- Nobel Prize, 1967)

Steady state treatment above is not applicable to fast reactions. However, relaxation techniques can be used to perturb the equilibrium and observed the return to a new equilibrium. The techniques are particularly useful for enzymes. Generally, they involve T (temperature) jump, P (pressure) jump, etc.

Consider the reversible reaction

$$A + B \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} P$$

where

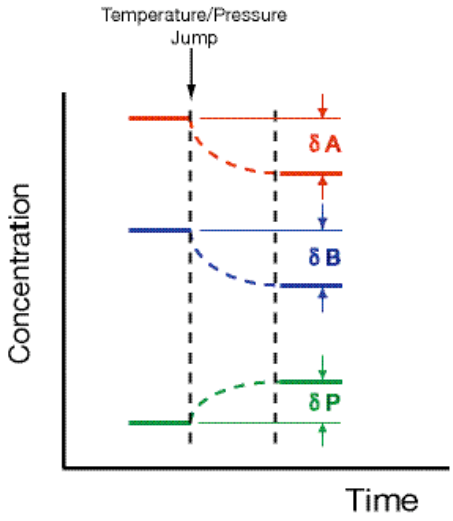
$$\frac{d[P]}{dt} = k_1[A][B] - k_{-1}[P] \qquad K = \frac{k_1}{k_{-1}} = \frac{[P]}{[A][B]}$$

Now, apply a T or P jump to the system and establish a new equilibrium according to

$$\left(\frac{\partial \Delta G}{\partial T}\right)_P = -\Delta S \quad \text{and} \quad \left(\frac{\partial \Delta G}{\partial P}\right)_T = \Delta V$$

$$\left(\frac{\partial \ln K}{\partial T}\right)_P = \frac{\Delta H^0}{RT^2} \quad \text{and} \quad \left(\frac{\partial \ln K}{\partial P}\right)_T = -\frac{\Delta V^0}{RT^2}$$

Experimentally a 5∞ Æ 10∞C or 10-$10^3$ atm change in $10^{-8}$ - $10^{-6}$ sec is achievable




$-\delta[A] = -\delta[B] = \delta[P]$ = are small, so we neglect quadratic terms.

For the above example,

$[P] = [\bar{P}] + \delta[P]$ where $[\bar{A}]$ & $[\bar{B}]$ are equilibrium values

$[A] = [\bar{A}] + \delta[A] = [\bar{A}] - \delta[P]$

$[B] = [\bar{B}] + \delta[B] = [\bar{B}] - \delta[P]$

$$\frac{d[P]}{dt} = \frac{d}{dt}\left([\bar{P}] + \delta[P]\right) = \frac{d(\delta[P])}{dt} \qquad \frac{d[\bar{P}]}{dt} = 0 \text{ -- small changes}$$

$$= k_1[A][B] - k_{-1}[P]$$

$$= k_1\left([\bar{A}] - \delta[P]\right)\left([\bar{B}] - \delta[P]\right) - k_{-1}\left([\bar{P}] + \delta[P]\right)$$

$$= k_1[\bar{A}][\bar{B}] - k_{-1}[\bar{P}] - k_1\left\{[\bar{A}]\,\delta[P] + [\bar{B}]\,\delta[P] - (\delta[P])^2\right\} - k_{-1}\delta[P]$$

which yields

$$-\frac{d(\delta[P])}{dt} = \left\{k_1([\bar{A}] + [\bar{B}]) + k_{-1}\right\}\delta[P]$$

or

$$-\frac{d(\delta[P])}{dt} = \frac{\delta[P]}{\tau}$$

where

$$\frac{1}{\tau} = k_1\left([\bar{A}] + [\bar{B}]\right) + k_{-1}$$

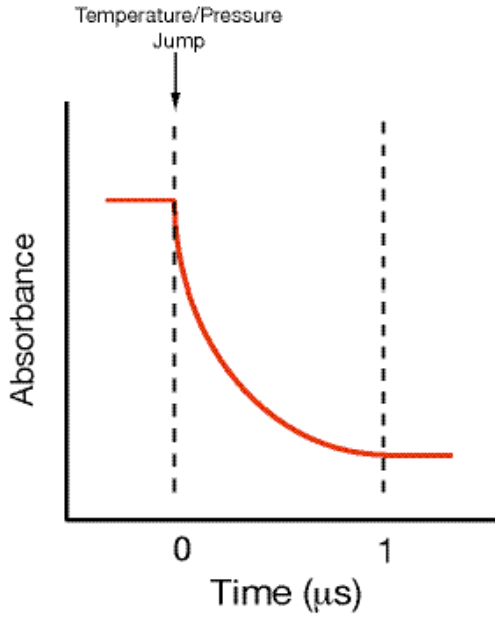
Integrating

$$\delta[P] = \delta[P]_0\, e^{-t/\tau}$$

where

$$\tau = \frac{1}{k_1\left([\bar{A}] + [\bar{B}]\right) + k_{-1}}$$ **Relaxation Tim**

An experiment typically consists of a T jump followed by a spectroscopic observation of relaxation.




Follow the optical absorbance, ESR line, NMR line, etc., after the T jump. Fit the experimental data to an exponential decay to obtain $\tau$.