Kinetics and Dynamics

Transition-state Theory (TST)

Video VII.viii
Transition-state Theory and Kinetics

Elementary Unimolecular Reactions

A \rightleftharpoons_{k_{\text{act}}} A^{\ddagger} \rightarrow_{k_{\ddagger}} B

\frac{d[A]}{dt} = k_1[A]

k_1 = \frac{k_B T}{h \cdot Q_A} \cdot e^{-\left(U_{A,0} - U_{A,0} \right)/k_B T}

Elementary Bimolecular Reactions

A + B \rightarrow C

\frac{d[A]}{dt} = k_1[A][B]

k_1 = \frac{k_B T}{h} \cdot \frac{Q_A \cdot Q_B}{Q_A^0 \cdot Q_B^0} \cdot e^{-\left(U_{A,0} - U_{A,0} - U_{B,0} \right)/k_B T}

In general:

k = \frac{k_B T}{h} \cdot \frac{Q_A^{\ddagger} \cdot Q_R^0}{Q_A^{\ddagger,0} \cdot Q_R} \cdot e^{-\Delta V^{\ddagger} / k_B T} = \frac{k_B T}{h} \cdot e^{-\Delta G^{\ddagger} / RT}

k_B is Boltzmann’s constant, \( h \) is Planck’s constant, \( T \) is temperature, \( Q \) is the partition function, and \( U_0 \) is the internal energy at 0 K (\( E + ZPVE \))
TST, Eyring, and Arrhenius Expressions

**TST**

\[
k = \frac{k_B T Q^\dagger}{h} \frac{Q_R^o}{Q_R^\dagger} e^{-\Delta V^\dagger / k_B T} = \frac{k_B T}{h} e^{-\Delta G^o / RT} = \frac{k_B T}{h} e^{-\Delta H^o / RT} e^{\Delta S^o / R}
\]

**Eyring**

\[
\ln\left(\frac{k}{T}\right) = -\frac{\Delta H^o,^\dagger}{RT} + \frac{\Delta S^o,^\dagger}{R} + \ln\left(\frac{k_B}{h}\right)
\]

Plot \(\ln(k / T)\) vs. \(1/T\)

**Arrhenius**

\[
k = Ae^{-E_a / RT}
\]

Plot \(\ln(k)\) vs. \(1/T\)

\[
E_a = \Delta H^o,^\dagger + RT \quad A = \frac{k_B T}{h} e^{(1 + \Delta S^o,^\dagger / R)}
\]

Be very careful making comparisons
What is a Block CoPolymer?

**Situation:**
Mixtures of two polymers—even seemingly *very* similar polymers—nearly always phase separate rather than "alloy"

**Consequence:**
If you want to design new materials that incorporate properties of both polymers on small length scales, you must keep the polymers from phase separating by covalently attaching chains of one type to chains of the other type, e.g., `AAAAAA BBBBBBB`

**Uses**
- Thermoplastic elastomers (e.g., running shoe soles)
- Pressure sensitive adhesives (Post-It™ Notes)
- Viscosity modifiers for oils
- Compatibilizers (the polymer equivalent of a soap)

**Challenge:**
How can you synthesize a well-defined BCP (e.g., having low polydispersity)?
One Technique for Making Fluorinated BCPs

- mild
- selective (no other insertion products)
- quantitative
- experimentally simple

\[
\begin{align*}
\text{F} & \text{O} & \text{CF}_3 \\
\text{F} & \text{F} & \text{F} \\
\text{F} & \text{O} & \text{CF}_3 \\
\text{F} & \text{F} & \text{F} \\
\end{align*}
\]

\[180 \, ^\circ \text{C}\]

\[
\begin{align*}
\text{F} & \text{C} & \text{F}_3 \\
\text{F} & \text{O} & \text{CF}_3 \\
\text{F} & \text{F} & \text{F} \\
\text{F} & \text{C} & \text{F}_3 \\
\end{align*}
\]

\[+\]

\[
\begin{align*}
\text{F} & \text{F} \\
\text{R}_1 & \text{R}_2 \\
\text{n} \\
\end{align*}
\]

\[
\begin{align*}
\text{F} & \text{F} \\
\text{R}_1 & \text{R}_2 \\
\text{n} \\
\end{align*}
\]

\[
\begin{align*}
\text{R}_1 & \text{R}_2 \\
\text{polyisoprene} & \text{H} & \text{Me} \\
\text{polybutadiene} & \text{H} & \text{H} \\
\text{polydimethylbutadiene} & \text{Me} & \text{Me} \\
\end{align*}
\]
If One Fluorine is Good... (E. I. DuPont)

Are there concerns?
Carbene Rearrangements in Hydrocarbons

1,3-\(\text{H}\) shift
\[ \Delta G^\ddagger = 8.3 \text{ kcal/mol} \]

1,2-\(\text{CH}_3\) shift
\[ \Delta G^\ddagger = 18.1 \text{ kcal/mol} \]

1,2-\(\text{H}\) shift
\[ \Delta G^\ddagger = 5.2 \text{ kcal/mol} \]
Kinetics 101

Carbene additions typically proceed without an activation barrier. The rates of barrierless reactions in solution are typically "diffusion controlled". Over a reasonable range of viscosities, an appropriate rate expression is:

\[ \text{Rate}_{\text{bi}} \text{ (M sec}^{-1}\text{)} \approx 10^{10} \cdot [A] [B] \]

Unimolecular rearrangements typically follow a particularly simple rate law:

\[ \text{Rate}_{\text{uni}} \text{ (M sec}^{-1}\text{)} \approx 10^{14} \cdot [A] \cdot \exp(-\Delta G^\ddagger / RT) \]

We would like the ratio of bimolecular reaction to unimolecular rearrangement to be at least a factor of 100, i.e.,

\[ \frac{\text{Rate}_{\text{bi}} \text{ (M sec}^{-1}\text{)}}{\text{Rate}_{\text{uni}} \text{ (M sec}^{-1}\text{)}} = 100 = 10^{-4} \cdot [B] \cdot \exp(\Delta G^\ddagger / RT) \]

Given a realistic maximum [B] (molar concentration of double bonds) of about 1 M, this implies the minimum activation energy for unimolecular rearrangement cannot be lower than 12.9 kcal/mol at 200 °C.
Carbene Rearrangements in Fluorocarbons

Because fluorine holds electrons more "tightly" than hydrogen, it is much harder to insert into C–F bonds than into C–H bonds. Interestingly, the accessibility of C–C bonds is relatively unperturbed by H vs. F.
Feasibility Study on Epoxide Cracking

\[ \Delta G^\ddagger = 32.0 \text{ kcal/mol} \]

\[ \Delta G^\ddagger = 46.7 \text{ kcal/mol} \]

Kinetics 102: Left path preferred by about 5,000,000 to 1 at 200 °C
Feasibility Study on Epoxide Cracking 2

Kinetics 103: Half-life for a unimolecular process (like cracking) is roughly

\[ t_{1/2} \text{ (sec)} \approx \ln 2 \cdot 10^{-14} \cdot \exp\left(\frac{\Delta G^\ddagger}{RT}\right) \]

For above reaction at 200 °C, 50% cracking takes 317 years . . . (4.8 hours for previous example via its preferred path)

Cramer and Hillmyer J. Org. Chem. 1999, 64, 4850
Kinetics and Dynamics

Kinetic Isotope Effects

Video VII.ix
Kinetic Isotope Effects

Very straightforward calculation

Primary KIE from difference in ZPVE from difference in change in ZPVE

Can be very useful for validating quality of computed transition-state structures
Protein Prenylation

Farnesylation of ras protein key to carcinogenesis

\[ c_f = 0.057 \text{ for PFT + GPP} \]

\[ 1^\circ \,^{13}\text{C KIE} = 1.039 \pm 0.003 \]

\[ 2^\circ \,^{2}\text{H KIE} = 1.068 \pm 0.003 \]

What is structure of transition state?
Choice of Theoretical Model (Validation)

$mPW1N/6-31+G(d)$ density functional theory

$\text{SN}_2$

\[ \text{KIE}_{\text{expt}} = 1.040 \pm 0.003 \]
\[ \text{KIE}_{\text{theor}} = 1.040 \]

$\text{SN}_1$

\[ \text{KIE}_{\text{expt}} = 0.997 \pm 0.003 \]
\[ \text{KIE}_{\text{theor}} = 1.001 \]
Modeling Prenylation

$mPW1N$ applied to GPP / ethanethiolate (aq)

\[ n = 1, \text{Farnesylidiphosphate} \]
\[ n = 0, \text{Geranylidiphosphate} \]

\[
1° \quad ^{13}\text{C KIE} = 1.039 \pm 0.003
\]
\[
2° \quad ^2\text{H KIE} = 1.068 \pm 0.003
\]

\[ S_{N2} \text{ process} \]
\[
1° \quad ^{13}\text{C KIE} = 1.067
\]
\[
2° \quad ^2\text{H KIE} = 1.150
\]
Controlling Making and Breaking Bonds

$1^\circ \ ^{13}\text{C KIE} = 1.039 \pm 0.003$

$2^\circ \ ^1\text{H KIE} = 1.068 \pm 0.003$
Active Site Influence on TS Structure

Looser — more ionic

Consistent with rate deceleration by electron-withdrawing groups
Kinetics and Dynamics

Tunneling, Variational Transition-state Theory (VTST), and Marcus Theory

Video VII.x
Quantum Effects on the Rate Constant
Reaction Probability Through a Parabolic Barrier

\[ k = \kappa(T) \frac{k_B T}{h} \frac{Q^\ddagger}{Q_R} \frac{Q_R^0}{Q_R^{\ddagger,0}} e^{-\Delta V^\ddagger / k_B T} \]
Tunneling and Eyring Plot Curvature

- **no tunneling**
- **turnover regime**
- **all tunneling**

\[ \ln k \]

\[ 1 / T \]
Tunneling in a Nutshell

• Typically only significant for reaction coordinates having large proton, H atom, or hydride motion
• Typically less significant at higher temperatures (but demonstrated to be important in many biological systems at *their* temperatures!)
• Accounting for tunneling is, frankly, hard, although the Skodje-Truhlar approximation is fairly straightforward
• Beware of experimental data that may be interpreted incorrectly because of a failure to consider tunneling!
Skodje-Truhlar

Parabolic Tunneling Calculations

Rex T. Skodje and Donald G. Truhlar*

Department of Chemistry and Chemical Physics Program, University of Minnesota, Minneapolis, Minnesota 55455
(Received: December 31, 1980)

A new analytic approximation is presented for thermally averaged transmission coefficients for tunneling through and reflection by truncated parabolic potential barriers. The approximation has a wide range of validity and avoids the spurious singularities of the well-known result for untruncated parabolic barriers. We also apply the analytic result to effective parabolic fits to other barrier shapes. The results are quite encouraging and suggest that the approximation may be useful for a wide variety of chemical applications.

\[ \kappa(T) = \begin{cases} \frac{\beta}{\beta - \alpha} \left\{ e^{\left[ (\beta - \alpha) (\Delta V^+ - V) \right]} - 1 \right\}, & \alpha \leq \beta \\ \frac{\beta \pi / \alpha}{\sin(\beta \pi / \alpha)} - \frac{\beta}{\alpha} e^{\left[ (\beta - \alpha) (\Delta V^+ - V) \right]}, & \alpha \geq \beta \end{cases} \]

\[ \alpha = \frac{2\pi}{\hbar \text{Im}(\nu^*)} \]

\[ \beta = \frac{1}{k_B T} \]
Methane Metathesis in Lutetiocene (kcal/mol)

\[
\ce{M-CH\textsubscript{3} + ^{13}\text{CH}_4 \rightleftharpoons M + CH\textsubscript{3} + ^{13}\text{CH}_4}
\]

\[\Delta H^\ddagger = \text{mPWPW91/ECP} \quad 20.3 \text{ kcal/mol}
\]

Eyring plot \quad 11.6

Sherer and Cramer

*Organometallics* **2003**, 22, 1682
# Fooled by Tunneling

<table>
<thead>
<tr>
<th>$T$, K</th>
<th>$k_{obs} \times 10^5$, s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>10.</td>
</tr>
<tr>
<td>330</td>
<td>67.</td>
</tr>
<tr>
<td>340</td>
<td>120.</td>
</tr>
<tr>
<td>350</td>
<td>200.</td>
</tr>
<tr>
<td>360</td>
<td>320.</td>
</tr>
<tr>
<td>370</td>
<td>510.</td>
</tr>
<tr>
<td>380</td>
<td>800.</td>
</tr>
<tr>
<td>390</td>
<td>1200.</td>
</tr>
<tr>
<td>400</td>
<td>1800.</td>
</tr>
</tbody>
</table>

$\Delta H^\ddagger = 11.6$  

$\Delta H^\ddagger = 19.2$  

DFT 20.3 kcal/mol
Variational Transition-state Theory

\[
k^\text{VTST}(T,s) = \min_s \frac{k_B T}{h} \frac{Q^\pm(T,s)}{Q_R} \frac{Q_R^0}{Q^\pm,o} e^{-\Delta V^\pm(s)/k_B T}
\]

s may be different for H and D (because Q is)
Electron Transfer—A Very Hard KIE Problem

\[ \Delta G^\circ = 0 \]

\[ \lambda/4 \]

\[ k_{ET} = Ze^{-\left(\Delta G^\circ + \lambda\right)^2/4\lambda RT} \]

Semiclassical effects in \( \Delta G^\circ \)

Quantum (tunneling) effects in \( Z \)
THANKS!!