CHAPTER 21: LECTURE NOTES FOR ORGANIC CHEMISTRY

CHEMICAL REACTIONS
- EQUATION: REACTANTS $\rightarrow$ PRODUCTS
- MECHANISM: STEP BY STEP PATHWAY
- THERMODYNAMICS: ENERGY FLOW
- KINETICS: RATES OF REACTION

THE FREE RADICAL CHLORINATION OF ALKANES

$$ \text{CH}_4 + \text{Cl}_2 \xrightarrow{\text{UV or HEAT}} \text{CH}_3\text{-Cl} + \text{H-Cl} $$

THE REACTION MAY CONTINUE
$$ \text{CH}_3\text{Cl} + \text{Cl}_2 \xrightarrow{\text{UV or HEAT}} \text{CH}_2\text{Cl}_2 + \text{HCl} $$
AND ON TO $\text{CH}_3\text{Cl}$ AND $\text{CCl}_4$

A CHAIN REACTION MECHANISM

INITIATION: $\text{Cl}^\cdot \xrightarrow{\text{UV}} \cdot\text{Cl}^\cdot + \cdot\text{Cl}^\cdot$

$\text{Cl}^\cdot$ is a FREE RADICAL
UNPAIRED ELECTRON
REACTIVE!

PROPAGATION

$$ \text{H} - \text{C}^\cdot - \text{H} + \text{Cl}^\cdot \rightarrow \text{H} - \text{C}^\cdot - \text{H} + \text{HCl} $$

$$ \text{H} - \text{C}^\cdot \rightarrow \text{H} - \text{C}^\cdot - \text{Cl}^\cdot $$

TERMINATION:

$$ \text{H} - \text{C}^\cdot + \text{Cl}^\cdot \rightarrow \text{H} - \text{C}^\cdot - \text{Cl}^\cdot $$

$$ 2 \text{Cl}^\cdot \rightarrow \text{Cl}_2 $$

$$ 2 \text{H} - \text{C}^\cdot \rightarrow \text{H} - \text{C}^\cdot - \text{C}^\cdot - \text{H} $$

This reaction has a very large $K_{28}$, $10^{19}$, so it will go to completion.

$$ \text{CH}_4 + \text{Cl}_2 \rightarrow \text{CH}_3\text{Cl} + \text{HCl} $$

USEFUL ENERGY FOR WORK: $\Delta G$

$$ \Delta G = -RT \ln K \quad \text{at } 25^\circ -RT = \frac{2.5}{2} $$

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

$\Delta H$ = ENTHALPY CHANGE
$\Delta S$ = ENTROPY CHANGE
Bond Dissociation Energy
All bonds have a characteristic energy (Table 4-2).

Energy is released when bonds are formed \( \Delta H - \)
Energy is consumed in breaking bonds \( \Delta H + \)

\( \Delta H \) for a reaction is the sum of the energy required to break bonds and the energy released by making bonds.

\[
\text{CH}_3 - \text{H} + \text{Cl} - \text{Cl} \rightarrow \text{CH}_3 - \text{Cl} + \text{H} - \text{Cl}
\]

\[
104 \text{ kcal/mol} \quad 58 \text{ kcal/mol} \quad -84 \text{ kcal/mol} \quad -103 \text{ kcal/mol}
\]

Broken = 162 kcal/mol \quad Made = -187 kcal/mol

\[
\text{Net} = -25 \text{ kcal/mol} \quad \text{Exothermic} \quad \Delta H -
\]

Kinetics

Kinetics is the study of rates of reaction.
Rates are expressed in a rate law \[ A + B \rightarrow C + D \]

\[
\text{Rate} = k[A]^a[B]^b
\]

Exponents must be determined experimentally.

A most useful concept is the order of a reaction.

Zero order — double [A] or [B] \( \rightarrow \) rate does not change
First order — double [A] or [B] \( \rightarrow \) rate doubles
Second order — double [A] or [B] \( \rightarrow \) rate quadruples

For a reaction, if \( \text{Rate} = k[A]^a[B]^b \) \( \rightarrow \) that's first order in A
Second order in B
Third order overall

The order of a reaction gives insight into its mechanism.

Activation energy, transition states, and reaction coordinate diagram.
RATES OF MULTI-STEP REACTIONS

THE STEP WITH THE HIGHEST ENERGY IS RATE DETERMINING FOR THE PROPAGATION STEPS:

\[ \text{CH}_4 + \text{Cl} \rightarrow \text{CH}_3 + \text{HCl} \quad \text{Eq} = 4 \text{ kcal/m} \]

\[ \text{CH}_3 + \text{Cl}_2 \rightarrow \text{CH}_3\text{Cl} + \text{Cl} \quad \text{Eq} = 1 \text{ kcal/m} \]

\[ \text{CH}_3 \text{ and Cl} \text{ are reactive intermediates produced in one step, consumed in another} \]

ISOTOPE EFFECTS

Deuterium is an isotope of hydrogen. Atomic number = 1, Atomic weight = 2

A C-D bond is slightly stronger (+2 kcal/m) than a C-H bond in our halogenation reaction:

\[ \text{CH}_3\text{D} + \text{Cl} \rightarrow \text{CH}_3\text{DCl} \rightarrow \text{CH}_3 + \text{DCl} \quad \text{Rate} = 1 \]

\[ \text{CO}_2\text{D} + \text{Cl} \rightarrow \text{CO}_2\text{DCl} \rightarrow \text{CO}_2 + \text{DCl} \quad \text{Rate} = \frac{1}{2} \]

TEMPERATURE DEPENDENCE OF HALOGENATION

<table>
<thead>
<tr>
<th>REACTION</th>
<th>Eq</th>
<th>RELATIVE RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>F$^-$ + CH$_4$ → HF + CH$_3$F</td>
<td>1.9 kcal</td>
<td>140,000</td>
</tr>
<tr>
<td>Cl$^-$ + CH$_4$ → HCl + CH$_3$Cl</td>
<td>4 kcal</td>
<td>1300</td>
</tr>
<tr>
<td>Br$^-$ + CH$_4$ → HBr + CH$_3$Br</td>
<td>18 kcal</td>
<td>9 x 10$^{-8}$</td>
</tr>
<tr>
<td>I$^-$ + CH$_4$ → HI + CH$_3$I</td>
<td>34 kcal</td>
<td>2 x 10$^{-19}$</td>
</tr>
</tbody>
</table>

CHLORINATION OF HIGHER ALKANES

PRODUCT RATIOS

\[ \text{CH}_3\text{CH}_2\text{CH}_3 + \text{Cl}_2 \xrightarrow{\text{UV}} \text{CH}_3\text{CH}_2\text{CH}_3 + \text{CH}_3\text{CH}_2\text{CH}_3 \]

RELATIVE REACTIVITY

\[ \frac{40\%}{6 \text{ primary hydrogens}} = \frac{40\%}{6} \]

\[ \frac{60\%}{2 \text{ secondary hydrogens}} = \frac{60\%}{2} \]

\[ \frac{30 \text{ Cl}^\circ}{4.5} \]

So a 2° H is 4.5x as reactive as a 1° H
THE RELATIVE REACTIVITY OF 1° AND 2° HYDROGENS REFLECTS THE RELATIVE STABILITY OF THE RADICALS

\[ \text{CH}_4 \rightarrow \text{CH}_3 + \text{H} \quad \Delta H = 104 \text{ Kcal} \]

\[ \text{CH}_3\text{CH}_2\text{CH}_3 \rightarrow \text{H} + \text{CH}_3\text{CH}_2\text{CH}_2 \quad \Delta H = 98 \text{ Kcal} \]

\[ \text{CH}_3\text{CH}_2\text{CH}_3 \rightarrow \text{H} + \text{CH}_3\text{CHCH}_3 \quad \Delta H = 95 \text{ Kcal} \]

\[ \text{C} = \cdot \text{H} \rightarrow \text{H} + \cdot \text{C} = \cdot \quad \Delta H = 91 \text{ Kcal} \]

TERTIARY > SECONDARY > PRIMARY > METHYL

A RCO SHOWS A LOWER \( E_r \) FOR 2° RADICALS AND A MORE EASILY ACHIEVED TRANSITION STATE

BROMINATION OF PROPAINE

THE RATE DETERMINING STEP IS ENDOOTHERMIC

1° BREAK \( \text{CH}_3\text{CH}_2\text{CH}_2 = \text{H} \) BOND \( \Delta H = +98 \text{ Kcal/m} \)

MAKE \( \text{CH}_3\text{CH}_2\text{CH}_2 - \text{CH} = \text{H} \) BOND \( \Delta H = -68 \text{ Kcal/m} \)

2° BREAK \( \text{C} = \cdot \text{C} = \cdot \) BOND \( \Delta H = 95 \text{ Kcal/m} \)

MAKE \( \cdot \text{C} = \cdot \text{C} = \cdot \) BOND \( \Delta H = -68 \text{ Kcal/m} \)

PRODUCT MIXTURE IS \( \text{CH}_3\text{CH}_2\text{CH}_2\text{B}_2 \text{Br} 3\% \)

\( \text{CH}_3\text{CH} \cdot \text{CH}_2 \text{Br} 97\% \)

3%/6 = 0.5%/H

97/6 = 48.5

SO 2° H ARE \( \frac{1}{5} = 97 \times \text{AS REACTIVE} \)
The relative reactivity of \(1^\circ\) and \(2^\circ\) hydrogens reflects the relative stability of the radicals.

\[ \text{CH}_4 \rightarrow \text{CH}_3^+ + \text{H}^- \quad \Delta H = 104 \text{ kcal} \quad \text{methyl} \]
\[ \text{CH}_3\text{CH}_2\text{CH}_3 \rightarrow \text{H}^+ + \text{CH}_3\text{CH}_2\text{CH}_2^- \quad \Delta H = 98 \text{ kcal} \quad \text{\(1^\circ\)} \]
\[ \text{CH}_3\text{CH}_2\text{CH}_3 \rightarrow \text{H}^+ + \text{CH}_3\text{CHCH}_3^- \quad \Delta H = 95 \text{ kcal} \quad \text{\(2^\circ\)} \]
\[ \text{C} - \text{C} - \text{H} \rightarrow \text{H}^+ + \text{C} - \text{C}^- \quad \Delta H = 91 \text{ kcal} \quad \text{\(3^\circ\)} \]

\[ \begin{align*}
\text{R} - \text{C}^- & \quad \text{R} - \text{C}^- \quad \text{H}^- \quad \text{H}^- \quad \text{STABILITY OF} \\
\text{R} & \quad \text{R} - \text{C}^- \quad \text{H}^- \quad \text{H}^- \quad \text{RADICALS} \\
\text{R} & \quad \text{R} - \text{C}^- \quad \text{R} - \text{C}^- \quad \text{H}^- \quad \text{H}^- \\
\text{R} & \quad \text{H}^- \quad \text{H}^- \\
\end{align*} \]

Tertiary > Secondary > Primary > Methyl

A RCO shows a lower \(E_a\) for \(2^\circ\) radicals and a more easily achieved transition state.

Transition state diagram:

- \(1^\circ\) about 1 kcal/m lower
- \(2^\circ\)
- \(3\) kcal lower

Bromination of propane

The rate determining step is endothermic.

\(1^\circ\)

- Break: \(\text{CH}_3\text{CH}_2\text{CH}_3\) bond \(\Delta H = +98\) kcal/m
- Make: \(\text{CH}_3\text{CH}_2\text{CH}_2\text{Br}\) bond \(\Delta H = -88\) kcal/m

\(2^\circ\)

- Break: \(\text{C} - \text{C} - \text{C}\) bond \(\Delta H = +10\) kcal/m
- Make: \(\text{C} - \text{C} - \text{C}\) bond \(\Delta H = -88\) kcal/m

Product mixture is \(\text{CH}_3\text{CH}_2\text{CH}_2\text{Br} 3\%\), \(\text{CH}_3\text{CH}_2\text{Br} 97\%\)

\[3% / C = 0.5% / H \]
\[97 / 2 = 48.5 \]

So \(2^\circ\) H are \(48.5 \div 97 = 97 \times\) as reactive.
DIELS-ALDER REACTION
SEE PROBLEM 51 FOR AN APPROACH TO THE ENOATE RULE

\[
\text{ene} + \text{ene} \rightarrow \text{ene}
\]

THE REACTION WORKS WELL WITH ALKynes AS DIENOPHILES

\[
\text{ene} + \text{ene} \rightarrow \text{ene}
\]
RING IS FUNCTIONALIZED FOR FURTHER REACTIONS, WHICH MAY INCLUDE RING OPENING

REACTIONS WITH UNSYMMETRICAL REALESNTS

THE ELECTRON WITHDRAWING GROUPS OF THE DIENOPHILE AND THE ELECTRON DONATING GROUPS OF THE DIENE USUALLY HAVE A 1,4 OR A 1,2 RELATIONSHIP IN THE PRODUCT, BUT NOT A 1,3 RELATIONSHIP

\[
\text{ene} + \text{ene} \rightarrow \text{ene} \quad \text{NOT} \quad \text{ene}
\]

1,4 PRODUCT

\[
\text{ene} + \text{ene} \rightarrow \text{ene} \quad \text{NOT} \quad \text{ene}
\]

1,3 PRODUCT

MOLECULAR ORBITALS AND PERICYCLIC REACTIONS

WHEN ATOMIC ORBITALS OVERLAP TO FORM BONDS, MOLECULAR ORBITALS ARE FORMED BY A LINEAR COMBINATION OF ATOMIC ORBITALS (LCAO).

SO, IN ETHYLENE, 2 p ORBITALS COMBINE TO FORM 2 MOLECULAR ORBITALS AND IN BUTADIENE, 4 p ORBITALS COMBINE TO FORM 4 MOLECULAR ORBITALS.

THE + AND - SIGNS REFER TO THE PHASE OF THE WAVE FUNCTION AND LOBES OF THE SAME SIGN OVERLAP CONSTRUCTIVELY. LOBES OF OPPOSITE SIGN OVERLAP DESTRUCTIVELY - CALLED ANTI BONDING.
THE DIELS-ALDER REACTION

A double bond can be electron-rich
\[ CH_3 \quad CH_3 \]
\[ C = C^x \]

Or electron-poor
\[ C = C \quad CH_3 \quad CH_3 \quad C - OH \]
\[ C = C \quad C = C^x \]

A very effective way to make C-membered rings is the DIELS-ALDER REACTION

In which we combine an electron-rich diene with an electron-poor alkene (or alkyne), called the dienophile

\[ \text{Diene} \quad \text{Dienophile} \]

concerted reaction

syn addition

STEREOCHEMISTRY

1) Diene is in S-cis conformation

2) Addition is syn

\( \text{Endo rule} \)

If there is a tt bond in the electron-withdrawing group

It is "endo" in the product
CHAPTER 21

RANK STABILITY OF CATIONS AND RADICALS

MECHANISM OF FREE RADICAL REACTIONS

REACTIVITY VS SELECTIVITY

UNDERSTAND HAMMOND POSTULATE

30, 31, 32, 4, 31, 1

23, 26

7, 8

7

SKIP SECTION 7, 10, 9, 8

CHAPTER 22

SECTION 6

DIELS-ALDER SYNTHESIS

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