Objectives

After completing this section, you should be able to

1. predict the value of $\Delta H^\circ$ for a gas-phase reaction, given the necessary bond dissociation energy data.
2. predict the dissociation energy of a particular bond, given $\Delta H^\circ$ for a reaction involving the bond and any other necessary bond dissociation energy data.
3. outline the limitations of using bond dissociation energies to predict whether or not a given reaction will occur.

Key Terms

Make certain that you can define, and use in context, the key terms below.

- bond dissociation energy
- solvation

Study Notes

The idea of calculating the standard enthalpy of a reaction from the appropriate bond dissociation energy data should be familiar to you from your first-year chemistry course.

Solvation is the interaction between solvent molecules and the ions or molecules dissolved in that solvent.

The homolytic bond dissociation energy is the amount of energy needed to break apart one mole of covalently bonded gases into a pair of radicals. The SI units used to describe bond energy are kiloJoules per mole of bonds (kJ/Mol). It indicates how strongly the atoms are bonded to each other.

Introduction

Breaking a covalent bond between two partners, A-B, can occur either heterolytically, where the shared pair of electron goes with one partner or another

$$[A-B \rightarrow A^+ + B^-]$$

or

$$[A-B \rightarrow A^+ + B^-]$$

or homolytically, where one electron stays with each partner.

$$[A-B \rightarrow A^\bullet + B^\bullet]$$

The products of homolytic cleavage are radicals and the energy that is required to break the bond homolytically is called the Bond Dissociation Energy (BDE) and is a measure of the strength of the bond.
Calculation of the BDE

The BDE for a molecule A-B is calculated as the difference in the enthalpies of formation of the products and reactants for homolysis

\[ \text{BDE} = \Delta_fH(A^\bullet) + \Delta_fH(B^\bullet) - \Delta_fH(A-B) \]

Officially, the IUPAC definition of bond dissociation energy refers to the energy change that occurs at 0 K, and the symbol is \( D_o \). However, it is commonly referred to as BDE, the bond dissociation energy, and it is generally used, albeit imprecisely, interchangeably with the bond dissociation enthalpy, which generally refers to the enthalpy change at room temperature (298K). Although there are technically differences between BDEs at 0 K and 298 K, those differences are not large and generally do not affect interpretations of chemical processes.

Bond Breakage/Formation

Bond dissociation energy (or enthalpy) is a state function and consequently does not depend on the path by which it occurs. Therefore, the specific mechanism in how a bond breaks or is formed does not affect the BDE. Bond dissociation energies are useful in assessing the energetics of chemical processes. For chemical reactions, combining bond dissociation energies for bonds formed and bonds broken in a chemical reaction using Hess's Law can be used to estimate reaction enthalpies.

Example 6.8.1: Chlorination of Methane

Consider the chlorination of methane

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

the overall reaction thermochemistry can be calculated exactly by combining the BDEs for the bonds broken and bonds formed

\[ \text{CH}_4 \rightarrow \text{CH}_3\bullet + \text{H}\bullet \text{ BDE(\text{CH}_3-\text{H})} \]
\[ \text{Cl}_2 \rightarrow 2\text{Cl}\bullet \text{ BDE(\text{Cl}_2)} \]
\[ \text{H}\bullet + \text{Cl}\bullet \rightarrow \text{HCl} \text{ BDE(\text{HCl})} \]
\[ \text{CH}_3\bullet + \text{Cl}\bullet \rightarrow \text{CH}_3\text{Cl} \text{ BDE(\text{CH}_3-\text{Cl})} \]

Hess's Law

\[ \text{\Delta H} = \text{BDE(\text{R-H})} + \text{BDE(\text{Cl}_2)} - \text{BDE(\text{HCl})} - \text{BDE(\text{CH}_3-\text{Cl})} \]

Because reaction enthalpy is a state function, it does not matter what reactions are combined to make up the overall process using Hess's Law. However, BDEs are convenient to use because they are readily available.
Alternatively, BDEs can be used to assess individual steps of a mechanism. For example, an important step in free radical chlorination of alkanes is the abstraction of hydrogen from the alkane to form a free radical.

\[
\text{RH} + \text{Cl}^* \rightarrow \text{R}^* + \text{HCl}
\]

The energy change for this step is equal to the difference in the BDEs in RH and HCl

\[
\Delta H = \text{BDE}(\text{R-H}) - \text{BDE}(\text{HCl})
\]

This relationship shows that the hydrogen abstraction step is more favorable when BDE(R-H) is smaller. The difference in energies accounts for the selectivity in the halogenation of hydrocarbons with different types of C-H bonds.

**Table 6.8.1: Representative C-H BDEs in Organic Molecules**

<table>
<thead>
<tr>
<th>R-H</th>
<th>D₀, kJ/mol</th>
<th>D₂⁹⁸, kJ/mol</th>
<th>R-H</th>
<th>D₀, kJ/mol</th>
<th>D₂⁹⁸, kJ/mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃-H</td>
<td>432.7±0.1</td>
<td>439.3±0.4</td>
<td>H₂C=CH-H</td>
<td>456.7±2.7</td>
<td>463.2±2.9</td>
</tr>
<tr>
<td>CH₃CH₂-H</td>
<td>423.0±1.7</td>
<td></td>
<td>C₆H₅-H</td>
<td>465.8±1.9</td>
<td>472.4±2.5</td>
</tr>
<tr>
<td>(CH₃)₂CH-H</td>
<td>412.5±1.7</td>
<td></td>
<td>HCCH</td>
<td>551.2±0.1</td>
<td>557.8±0.3</td>
</tr>
<tr>
<td>(CH₃)₃C-H</td>
<td>403.8±1.7</td>
<td></td>
<td>H₂C=CHCH₂-H</td>
<td>371.5±1.7</td>
<td></td>
</tr>
<tr>
<td>HC(O)-H</td>
<td>368.6±0.8</td>
<td></td>
<td>C₆H₅CH₂-H</td>
<td>375.3±2.5</td>
<td></td>
</tr>
<tr>
<td>CH₃C(O)-H</td>
<td>374.0±1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Trends in C-H BDEs**

It is important to remember that C-H BDEs refer to the energy it takes to break the bond, and is the difference in energy between the reactants and the products. Therefore, it is not appropriate to interpret BDEs solely in terms of the "stability of the radical products" as is often done.

Analysis of the BDEs shown in the table above shows that there are some systematic trends:

1. **BDEs vary with hybridization:** Bonds with sp³ hybridized carbons are weakest and bonds with sp hybridized carbons are much stronger. The vinyl and phenyl C-H bonds are similar, reflecting their sp² hybridization. The correlation with hybridization can be viewed as a reflection of the C-H bond lengths. Longer bonds formed with sp³ orbitals are consequently weaker. Shorter bonds formed with orbitals that have more s-character are similarly stronger.

2. **C-H BDEs vary with substitution:** Among sp³ hybridized systems, methane has the strongest C-H bond. C-H bonds on primary carbons are stronger than those on secondary carbons, which are stronger than those on tertiary carbons.
Interpretation of C-H BDEs for sp\(^3\) Hybridized Carbons

The interpretation of the BDEs in saturated molecules has been subject of recent controversy. As indicated above, the variation in BDEs with substitution has traditionally been interpreted as reflecting the stabilities of the alkyl radicals, with the assessment that more highly substituted radicals are more stable, as with carbocations. Although this is a popular explanation, it fails to account for the fact the bonds to groups other than H do not show the same types of variation.

<table>
<thead>
<tr>
<th>R</th>
<th>BDE(R-CH(_3))</th>
<th>BDE(R-Cl)</th>
<th>BDE(R-Br)</th>
<th>BDE(R-OH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(_3)-</td>
<td>377.0±0.4</td>
<td>350.2±0.4</td>
<td>301.7±1.3</td>
<td>385.3±0.4</td>
</tr>
<tr>
<td>CH(_3)CH(_2)-</td>
<td>372.4±1.7</td>
<td>354.8±2.1</td>
<td>302.9±2.5</td>
<td>393.3±1.7</td>
</tr>
<tr>
<td>(CH(_3))(_2)CH-</td>
<td>370.7±1.7</td>
<td>356.5±2.1</td>
<td>309.2±2.9</td>
<td>399.6±1.7</td>
</tr>
<tr>
<td>(CH(_3))(_3)C-</td>
<td>366.1±1.7</td>
<td>355.2±2.9</td>
<td>303.8±2.5</td>
<td>400.8±1.7</td>
</tr>
</tbody>
</table>

Therefore, although C-CH\(_3\) bonds get weaker with more substitution, the effect is not nearly as large as that observed with C-H bonds. The strengths of C-Cl and C-Br bonds are not affected by substitution, despite the fact that the same radicals are formed as when breaking C-H bonds, and the C-OH bonds in alcohols actually increase with more substitution.

Gronert has proposed that the variation in BDEs is alternately explained as resulting from destabilization of the reactants due to steric repulsion of the substituents, which is released in the nearly planar radicals.\(^1\) Considering that BDEs reflect the relative energies of reactants and products, either explanation can account for the trend in BDEs.

Another factor that needs to be considered is the electronegativity. The Pauling definition of electronegativity says that the bond dissociation energy between unequal partners is going to be dependent on the difference in electronegativities, according to the expression

\[
[D_o(A-B) = \frac{D_o(A-A) + D_o(B-B)}{2} + (\langle X_A \rangle - \langle X_B \rangle)^2]
\]

where \(\langle X_A \rangle\) and \(\langle X_B \rangle\) are the electronegativities and the bond energies are in eV. Therefore, the variation in BDEs can be interpreted as reflecting variation in the electronegativities of the different types of alkyl fragments.

There is likely some merit in all three interpretations. Since Gronert's original publication of his alternate explanation, there have been many desperate attempts to defend the radical stability explanation.

References

Further Reading

*Master Organic Chemistry*

**Bond Strengths And Radical Stability**

**Exercises**

1. Given that $\Delta H^\circ$ for the reaction

   $\text{CH}_4 (g) + 4\text{F}_2 (g) \rightarrow \text{CF}_4 (g) + 4\text{HF} (g)$

   is ~1936 kJ, use the following data to calculate the average bond energy of the $\text{C}-\text{F}$ bonds in $\text{CF}_4$.

<table>
<thead>
<tr>
<th>Bond</th>
<th>Average Bond Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C-H}$</td>
<td>413 kJ · mol$^{-1}$</td>
</tr>
<tr>
<td>$\text{F-F}$</td>
<td>155 kJ · mol$^{-1}$</td>
</tr>
<tr>
<td>$\text{H-F}$</td>
<td>567 kJ · mol$^{-1}$</td>
</tr>
</tbody>
</table>

   Bonds broken:
   
   $4 \text{ mol } \text{C-H} \text{ bonds} \times \left(\frac{413 \text{ kJ}}{1 \text{ mol}}\right) = 1652 \text{ kJ}$
   
   $4 \text{ mol } \text{F-F} \text{ bonds} \times \left(\frac{155 \text{ kJ}}{1 \text{ mol}}\right) = 620 \text{ kJ}$

   Bonds formed:
   
   $4 \text{ mol } \text{C-F} \text{ bonds} \times \left(\frac{x \text{ kJ}}{1 \text{ mol}}\right) = 4x \text{ kJ}$

   (where $x$ = the average energy of one mole of $\text{C-F}$ bonds in $\text{CF}_4$, expressed in kJ)

2. Calculate $\Delta H^\circ$ for the reactions given below.
   
   a. $\text{CH}_3\text{CH}_2\text{OCH}_3 + \text{HI} \rightarrow \text{CH}_3\text{CH}_2\text{OH} + \text{CH}_3\text{I}$
   
   b. $\text{CH}_3\text{Cl} + \text{NH}_3 \rightarrow \text{CH}_3\text{NH}_2 + \text{HCl}$

**Answers:**

1. $\text{CH}_4(g) + 4\text{F}_2(g) \rightarrow \text{CF}_4(g) + 4\text{HF}(g)$ $\Delta H^\circ = -416 \text{ kcal}$

   Bonds broken:
   
   $4 \text{ mol } \text{C-H} \text{ bonds} \times \left(\frac{413 \text{ kJ}}{1 \text{ mol}}\right) = 1652 \text{ kJ}$
   
   $4 \text{ mol } \text{F-F} \text{ bonds} \times \left(\frac{155 \text{ kJ}}{1 \text{ mol}}\right) = 620 \text{ kJ}$

   Bonds formed:
   
   $4 \text{ mol } \text{C-F} \text{ bonds} \times \left(\frac{x \text{ kJ}}{1 \text{ mol}}\right) = 4x \text{ kJ}$

   (where $x$ = the average energy of one mole of $\text{C-F}$ bonds in $\text{CF}_4$, expressed in kJ)
\[4 \text{ mol} \left\{ \text{lsf[H-F]} \right\} \text{ bonds} \times \frac{(567 \text{ kJ})}{(1 \text{ mol})} = 2268 \text{ kJ}\]

\[\Delta H^\circ = \Delta H^\circ \text{ (bonds broken)} - \Delta H^\circ \text{ (bonds formed)}\]

\[= (1652 \text{ kJ} + 620 \text{ kJ}) - (4x + 2268 \text{ kJ})\]

\[= 1652 \text{ kJ} + 620 \text{ kJ} - 4x - 2268 \text{ kJ}\]

\[= -1936 \text{ kJ}\]

Thus,

\[4x = 1936 \text{ kJ} - 2268 \text{ kJ} + 620 \text{ kJ} + 1652 \text{ kJ}\]

\[= 1940 \text{ kJ}\]

and

\[x = \frac{1940 \text{ kJ}}{4 \text{ mol}}\]

\[= 385 \text{ kJ} \cdot \text{mol}^{-1}\]

The average energy of a \(\{\text{lsf[C-F]}\}\) bond in CF\(_4\) is 385 kJ \cdot \text{mol}^{-1}

2. a. \(\{\text{CH3CH2OCH3} + \text{HI} \rightarrow \text{CH3CH2OH} + \text{CH3I}\}\)

\[\begin{array}{c|c} \text{Reactant bonds broken} & D \\ \hline \text{C-H} & 339 \text{ kJ/mol} \\ \text{C-H} & 298 \text{ kJ/mol} \\ \hline \text{Product bonds formed} & D \\ \hline \text{C-H} & 436 \text{ kJ/mol} \\ \text{H-Cl} & 234 \text{ kJ/mol} \\ \hline \end{array}\]

\[\Delta H^\circ = D_{\text{bonds broken}} + D_{\text{bonds formed}}\]

\[= 637 \text{ kJ/mol} - 670 \text{ kJ/mol}\]

\[= -33 \text{ kJ/mol}\]

b. \(\{\text{CH3Cl} + \text{NH3} \rightarrow \text{CH3NH2} + \text{HCl}\}\)

\[\begin{array}{c|c} \text{Reactant bonds broken} & D \\ \hline \text{C-H} & 351 \text{ kJ/mol} \\ \text{N-H} & 449 \text{ kJ/mol} \\ \hline \text{Product bonds formed} & D \\ \hline \text{C-N} & 335 \text{ kJ/mol} \\ \text{H-Cl} & 432 \text{ kJ/mol} \\ \hline \end{array}\]

\[\Delta H^\circ = D_{\text{bonds broken}} + D_{\text{bonds formed}}\]

\[= 800 \text{ kJ/mol} - 767 \text{ kJ/mol}\]

\[= +33 \text{ kJ/mol}\]
Contributors

- Dr. Dietmar Kennepohl FCIC (Professor of Chemistry, Athabasca University)
- Prof. Steven Farmer (Sonoma State University)
- Prof. Paul G. Wenthold (Purdue University)