**Chemistry 5.12 Spring 2003, 3/7/03**
**Handout #8: Lecture 12**

## Outline

- E. Chlorination of Propane **(4-13)**
  - 1. Inequivalent Hydrogens (1°,2°,3°) **(3-3)**
  - 2. Relative Reactivity **(4-13A)**
  - 3. Selectivity
- F. Bromination of Propane **(4-13C)**
  - 1. Selectivity (Hammond Postulate) **(4-14)**
- G. Radical Stability **(4-13B, 4-16)**
- H. General Selectivity of Radical Halogenations

**Suggested Problems:** 4-39,41,44–46,54

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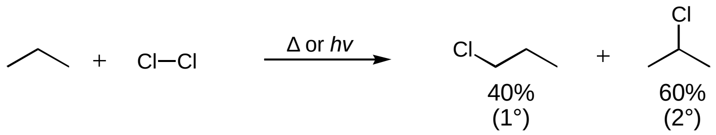
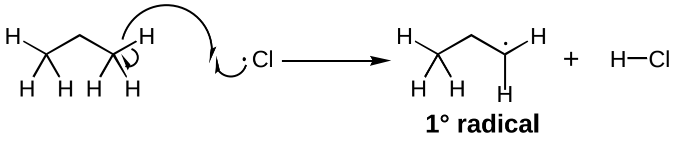
## E. Radical Chlorination of Propane: Inequivalent Hydrogens



There are two possible products! Why?

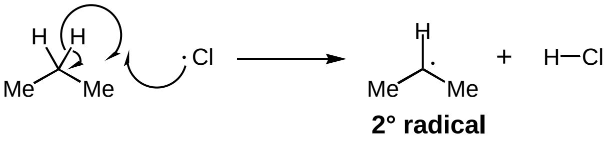
- Propane has two **inequivalent** types of hydrogens that can be abstracted in the first propagation step.
- The first propagation step determines which product will be formed (1° or 2°).

**Primary (1°):** There are six primary hydrogens.



- Abstraction of a primary hydrogen leads to the primary product.

**Secondary (2°):** There are two secondary hydrogens.



- Abstraction of a secondary hydrogen leads to the secondary product.

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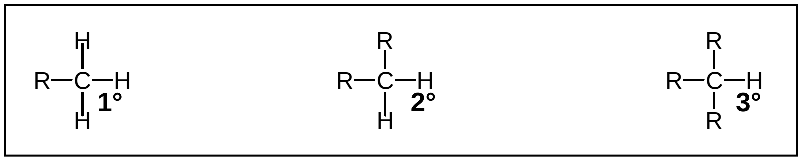
## 1. Inequivalent Hydrogens (1°, 2°, 3°)

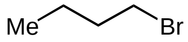
**Primary (1°) Carbon:** carbon that has only one other carbon attached to it

**Secondary (2°) Carbon:** carbon that has two other carbons attached to it

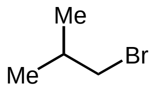
**Tertiary (3°) Carbon:** carbon that has three other carbons attached to it



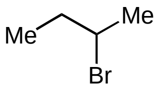
- We also refer to substituents as primary, secondary or tertiary.



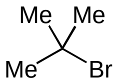
*n*-butyl bromide (**1°**)



*iso*-butyl bromide (**1°**)



***sec***-butyl bromide (**2°**)



***tert***-butyl bromide (**3°**)

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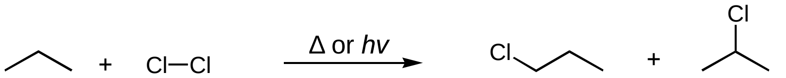
### Radical Chlorination of Propane (cont.)



**1°** (40%)  **2°** (60%)

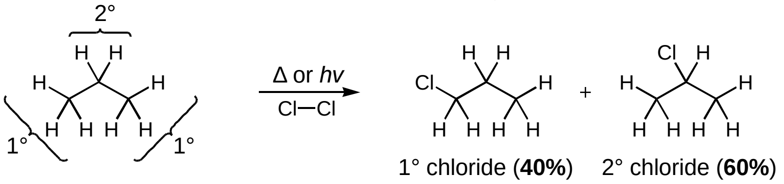
- There are **six primary** hydrogens and **two secondary** hydrogens, but the secondary chloride is favored.

- How can we explain the selectivity of this reaction?

- Radical formation is under **kinetic control**, so abstraction of the 2° hydrogen to form the 2° radical must be **faster** than abstraction of the 1° hydrogen to form the 1° radical.

- **In other words, the secondary hydrogens are more reactive than the primary hydrogens under these conditions!**

## 2. Relative Reactivity



1° chloride (**40%**) 2° chloride (**60%**)

**Calculating Relative Reactivity:**

**primary:** $\frac{40\%}{6 \text{ H's}} = 6.67\%$ per H

**secondary:** $\frac{60\%}{2 \text{ H's}} = 30.0\%$ per H

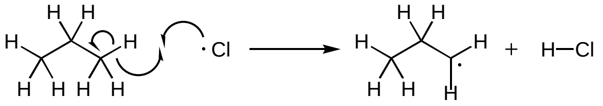
$$\frac{\textbf{secondary}}{\textbf{primary}} = \frac{30.0}{6.67} = 4.5$$

**• The secondary hydrogens are 4.5 times more reactive than the primary hydrogens.**

**Why?**

**We can answer this using thermodynamics, kinetics, and reaction-energy diagrams!**

**Primary:**

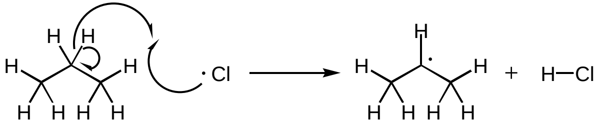


**1° radical**

form H–Cl: –103 kcal/mol
break 1° C–H: +98 kcal/mol

overall: ΔH° = –5 kcal/mol

**Secondary:**



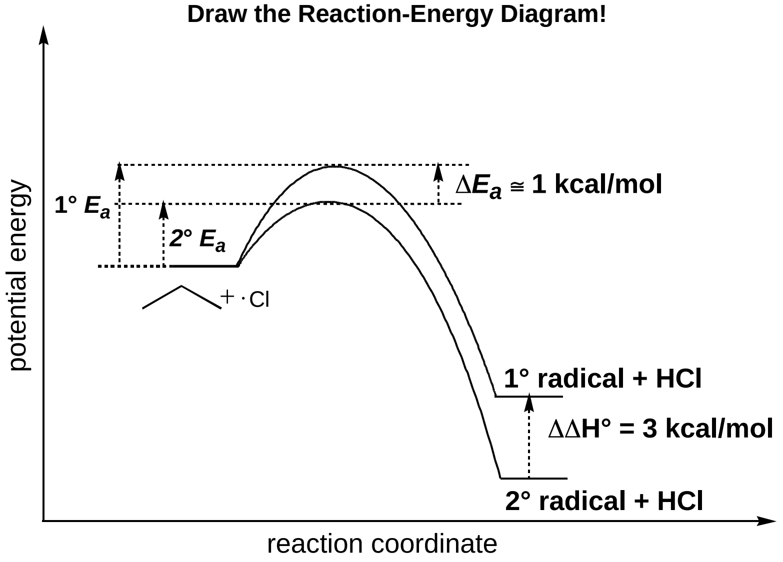
**2° radical**

form H–Cl: –103 kcal/mol
break 2° C–H: +95 kcal/mol

overall: ΔH° = –8 kcal/mol

- **2° C–H bonds are weaker than 1° C–H bonds.**
- This means that it is **thermodynamically** more favorable to break a 2° C–H bond than a 1° C–H bond.
- But how does this control the **kinetic** selectivity?

### Draw the Reaction-Energy Diagram!



- This reaction is under **kinetic control**, so the product ratio is determined by $\Delta E_a$.
- **How can you predict the value of $\Delta E_a$?**

### Analyze the Reaction-Energy Diagram!

**Comparing the transition states for the two products:**

- The energy of a transition state will always depend, to differing extents, on the energies of the reactants and the products.

- In this case, the reactants are the same for both processes (same energy).

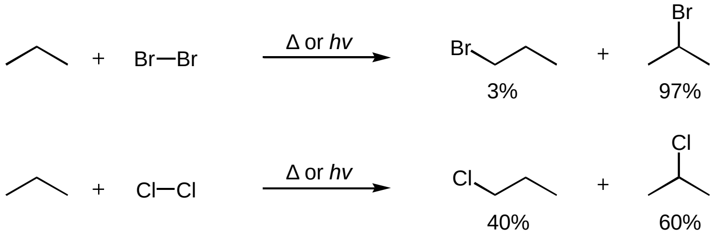
- The only energy difference is in the products: the 2° radical is lower in energy than the 1° radical.

- This means that the transition state leading to formation of the 2° radical is slightly lower in energy than the transition state leading to formation of the 1° radical.

- **The secondary radical is formed faster!**

- **It is important to remember that $\Delta E_a$ depends on, but will never exceed ΔΔH°!**

## F. Bromination of Propane: Higher Selectivity



- Radical brominations are generally much more selctive than radical halogenations.
  - How can we explain this difference?
    - Let's start with thermodynamics!

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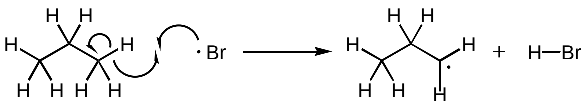
- Look at the propagation steps:

**Primary:**

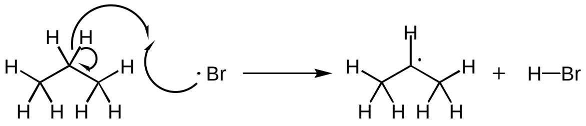


**1° radical**

form H–Br: –88 kcal/mol
break 1° C–H: +98 kcal/mol

overall: ΔH° = +10 kcal/mol

**Secondary:**



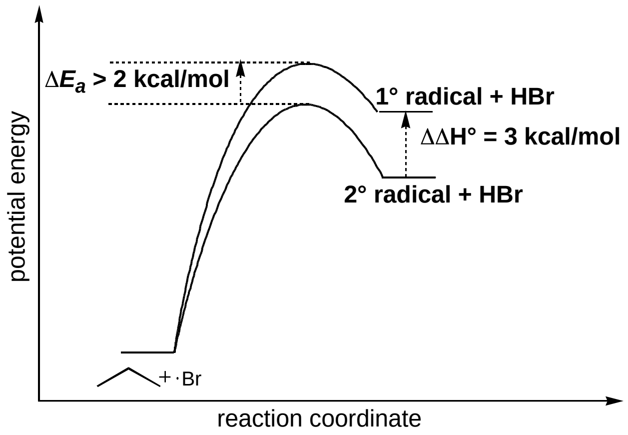
**2° radical**

form H–Br: –88 kcal/mol
break 2° C–H: +95 kcal/mol

overall: ΔH° = +7 kcal/mol

- The H–Br bond (BDE = 88 kcal/mol) is much weaker than the H–Cl bond (BDE = 103 kcal/mol).
- **HYDROGEN ABSTRACTION WITH Br· IS ENDOTHERMIC!**

## Reaction-Energy Diagram : Bromination of Propane (Propagation Step #1)



- This diagram looks **slightly** similar to the one we drew for the chlorination of propane.
- The big difference is that this step is now **endothermic**. So what?
- **THINK HAMMOND POSTULATE!**

**Remember the Hammond Postulate:**

- In an **exothermic** reaction, the transition state more closely resembles the **reactants**.
- In an **endothermic** reaction, the transition state more closely resembles the **products**.

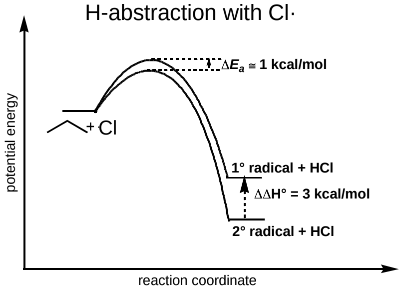
**What this means:**

- The 3 kcal/mol energy difference between the 1° and 2° radicals will have the biggest effect on the transition state energies in the **endothermic abstraction with bromine.**

- This is why radical brominations are more selective than radical chlorinations!

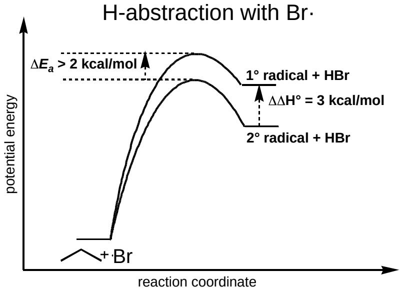
## Reaction-Energy Diagrams: Chlorination versus Bromination of Propane (Propagation Step #1)

H-abstraction with Cl·



**exothermic**

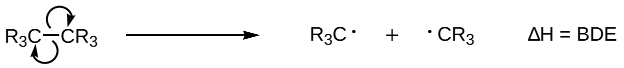
H-abstraction with Br·



**endothermic**
**(more selective)**

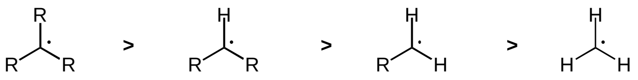
## G. RADICAL STABILITY!

**Why is it easier to break a 2° C–H bond than a 1° C–H bond?**



- Bond dissociation energies depend on radical stability.
- It's easier to homolytically cleave a bond when more stable radicals are formed.

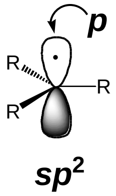
**Radical Stability:**



Tertiary (3°) > Secondary (2°) > Primary (1°) > Methyl

**To understand this trend, we need to take a closer look at the electronic structure of a radical.**

**Closer look at a radical. . .**



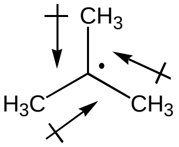
- Radicals are **electron-deficient** because they have less than an octet.

- As you might expect based on this, radical stability depends on hybridization (effective electronegativity).
**Stability: $sp^3 > sp^2 > sp$**

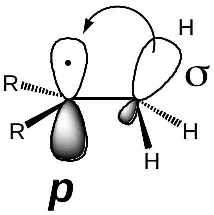
- Alkyl groups stabilize electron-deficient radicals by donating electron density in two ways: **induction** and **hyperconjugation**.

**1. Alkyl groups are inductive electron-donating groups (EDGs).**

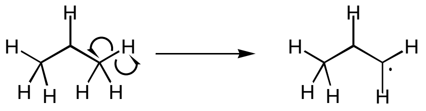
- Alkyl substituents donate electron density through the sigma-bond framework.



**2. Hyperconjugation:** Alkyl groups stabilize radicals through overlap between filled $\sigma_{C-H}$ orbitals and the half-filled *p*-orbital.

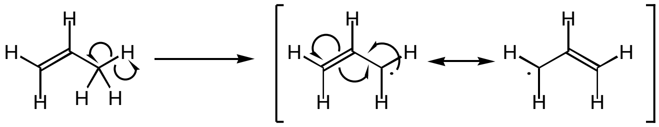


**Radicals are also stabilized by resonance!**
**(just like positive and negative charges)**



propane

**BDE = 98 kcal/mol**



propene

**allylic radical**

**BDE = 87 kcal/mol**

- The allylic radical is more stable because of resonance.
  DELOCALIZATION = STABILIZATION

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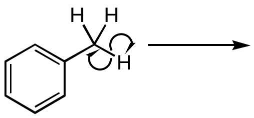
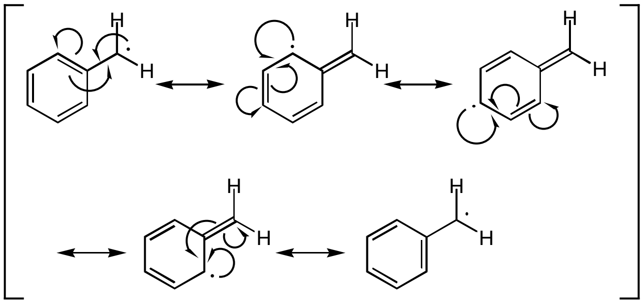
**Resonance Stabilized Radicals**



toluene

**BDE = 85 kcal/mol**



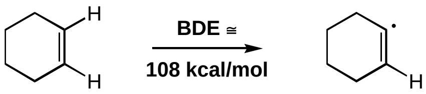
**benzylic radical**

## H. General Selectivity of Radical Halogenations

- Radical brominations are highly selective when one type of hydrogen is particularly reactive (resonance-stabilized).

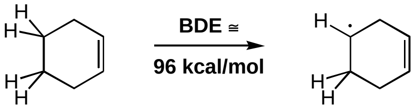
**eg. Cyclohexene has thre types of hydrogens:**

***sp*$^2$**



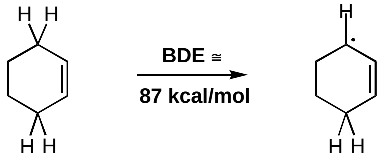
- **BAD:** *sp*$^2$ Radicals are unstable.

**2°**



- **OKAY:** These hydrogens act like regular 2° hydrogens.

**allylic**



- **GOOD:** This radical is delocalized (stabilized by resonance).

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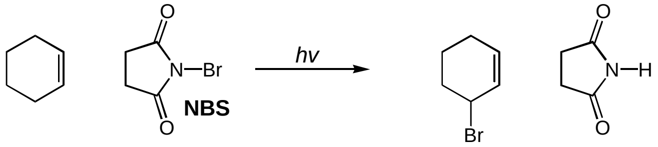
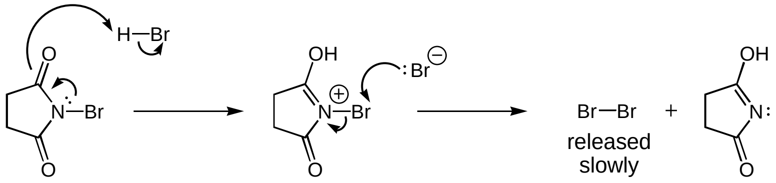
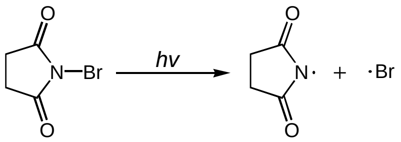
- The radical halogenation of cyclohexene is selective, **BUT** cyclohexene can react with $Br_2$ in other ways when the concentration of $Br_2$ is too high.
  - *N*-Bromosuccinimide (**NBS**) is used because it releases bromine **slowly**.





But how does it start?



- The initially formed bromine radical abstracts a hydrogen from cyclohexene to form cyclohexyl radical and HBr.
  - This starts the chain!