POLITECNICO DI MILANO

Department CMIC

Lecture 5 – FR5





Free-Radicals: Chemistry and Biology

Prof. Attilio Citterio
Dipartimento CMIC “Giulio Natta”
http://iscamap.chem.polimi.it/citterio/education/free-radical-chemistry/

Content

1. **Introduction**
   - Current Status of Radicals Chemistry
   - What is a Radical
   - Free Radicals and Life
2. **Historical Aspects**
3. **Electronic Structure and Bonding**
4. **Active Oxygen Specie,**
   - O_2, $O_2^{\bullet -}$, $HO_2^{\bullet}$, $^1O_2$, H_2O_2, $HO^{\bullet}$
   - Chemistry
   - H_2O_2 and peroxides
5. **Radical Reactions**
   - Atom transfer
   - Addition to multiple bonds
   - Homolytic Aromatic Substitution
   - Electron Transfer (oxidation-reduction)
6. **Thermodynamics**
7. **Free Radical Kinetics**
   - First-order Reaction
   - Second-order Reaction
   - Steady-State
   - Chain-reactions
   - Redox chain reactions
   - Inhibition
8. **Radiation Chemistry**
   - Tools
   - Specie: e^-(aq), $H^{\bullet}$, $HO^{\bullet}$, H_2O_2, H_2, $O_2^{\bullet -}$
   - Pulse Radiolysis/Flash Photolysis
9. **Lipid Peroxidation**
   - Chemistry
   - Measurement
   - Effects
10. **Antioxidants**
    - Preventive
    - Chain-breaking
    - Small molecule (Vit. C/E, CoQ, Urate).
    - Enzymes
    - Chelates
11. **Metals and Free Radical Chemistry**
    - Reactions
    - Complexes and redox chemistry
12. **DNA and Protein** (As radical targets)
13. **Photo reactions**
    - Photochemistry
    - Photosensitization
14. **Detection of Radicals**
    - TBARS
    - Fluorescence
    - Cyt. C /NBT
    - Strategies 1. SOD, CAT
15. **EPR Detection of Radicals**
    - Direct Detection
    - Spin Trapping
    - Transition metal
16. **Nitric Oxide/NOS**
17. **Oxygen radicals/ROS**

POLITECNICO DI MILANO





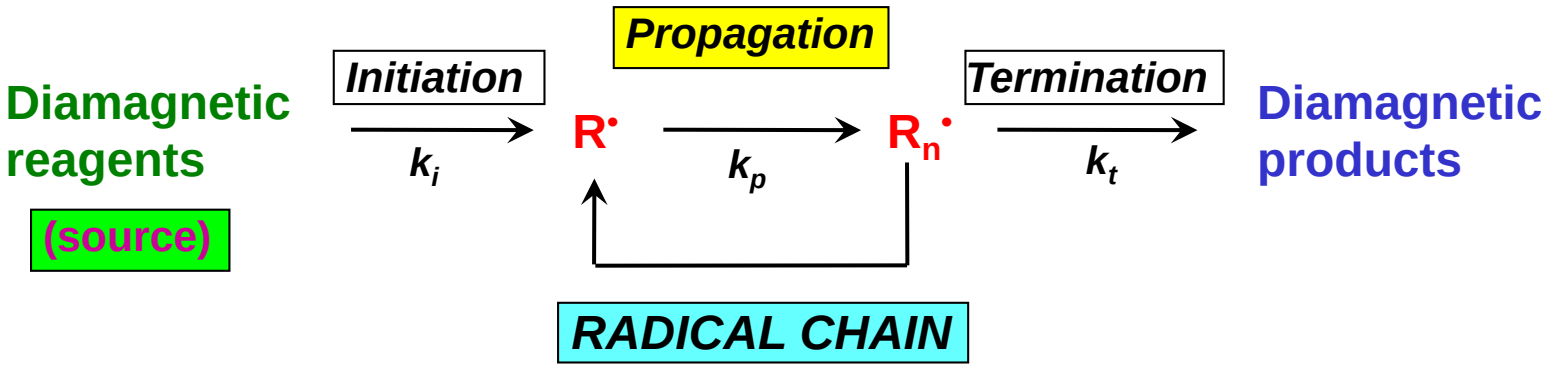
Free Radical Reactions

Prof. Attilio Citterio
Dipartimento CMIC “Giulio Natta”

Radical Reactions

Molecular transformation involving paramagnetic species.

Mechanism:



Initiation : generation of paramagnetic species from diamagnetic precursors

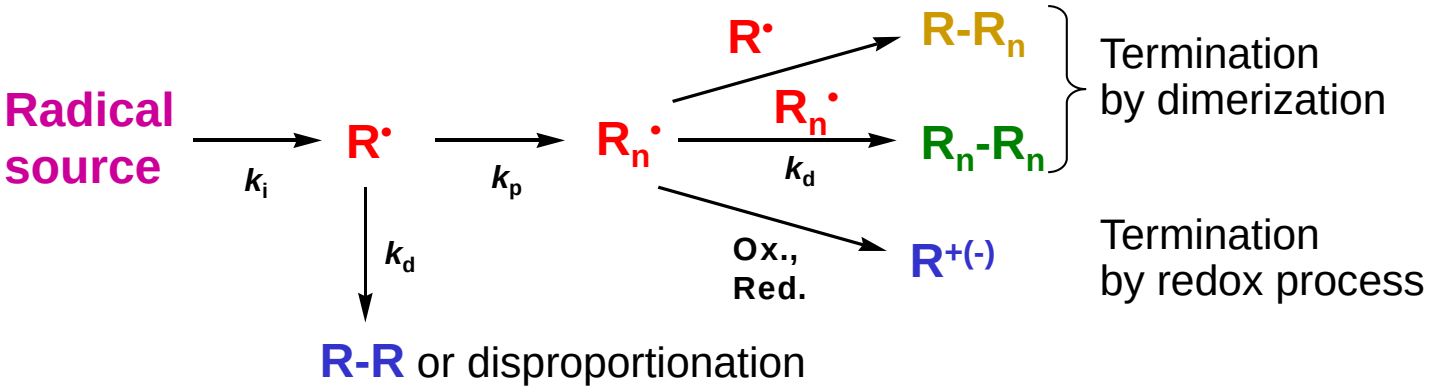
Propagation : migration of the radical center from an atom to another

Termination : disappearance of paramagnetic species.

Radical chain : regeneration of a paramagnetic specie from another involved in the propagation step.

Free Radical Non-Chain Reactions

A) Absence of chain (stoichiometric process in the radical source)



k_d ~ 10^9 $M^{-1}\cdot s^{-1}$ at 25°C (diffusion controlled in common solvents)

v = 1 $M^{-1}\cdot s^{-1}$ at 25°C , [R•] = 10^{-5} M (steady state)

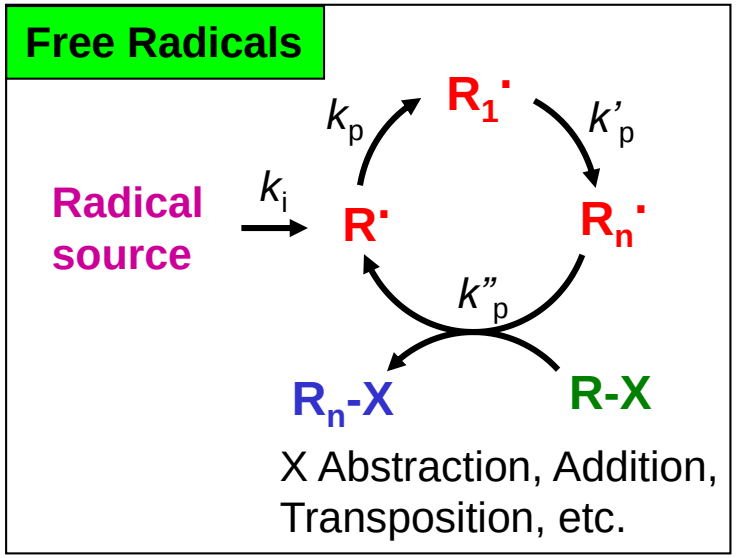
Radical Inhibitor (A): a compound able to prevent radical chain processes. The processes become stoichiometric in the radical source.

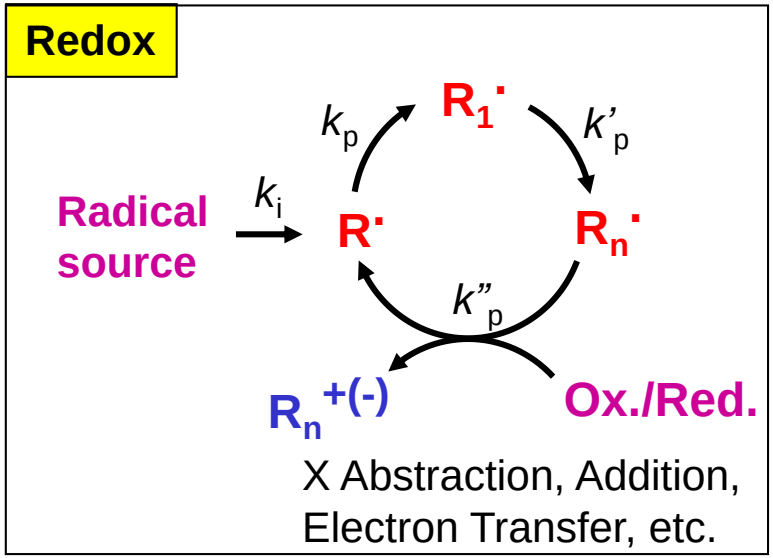
a) Generates persistent radicals (R-R_n process)

b) Generates stabilized radicals (R_n-R_n process)

The Main Mechanistic Alternatives

Catalytic Sources : CHAIN PROCESSES





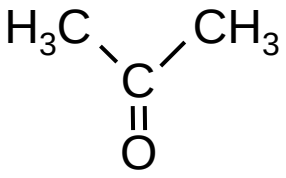
Stoichiometric Sources : INHIBITED PROCESSES

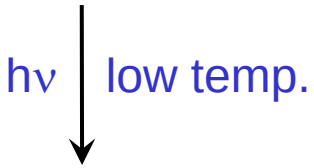
Characteristics of Radical Reactions

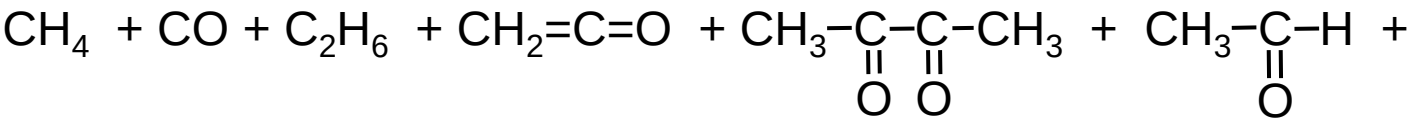
- Radical reactions occur readily in solid, liquid and gas phases
- Radical reactions generally are not influenced by solvent polarity
- Radical reactions generally are not influenced by acid or base catalysis
- Unlike cations or anions, radicals generally are scantly influenced by electron-donating or electron-withdrawing substituents
- Radical reactions are often preceded by an induction period during which time they are subject to inhibition
- Radical reactions are frequently chain processes
- Radical reactions are not frequently accompanied by skeletal rearrangements

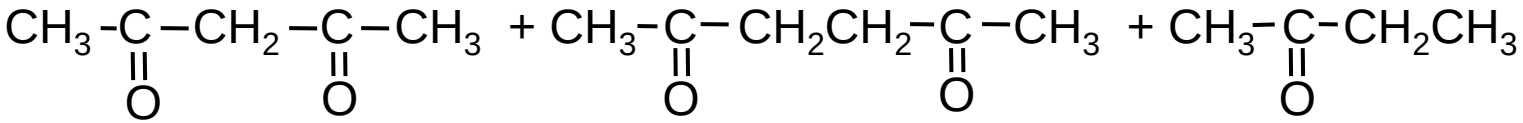
A Typical Free Radical Reaction

Overall reaction

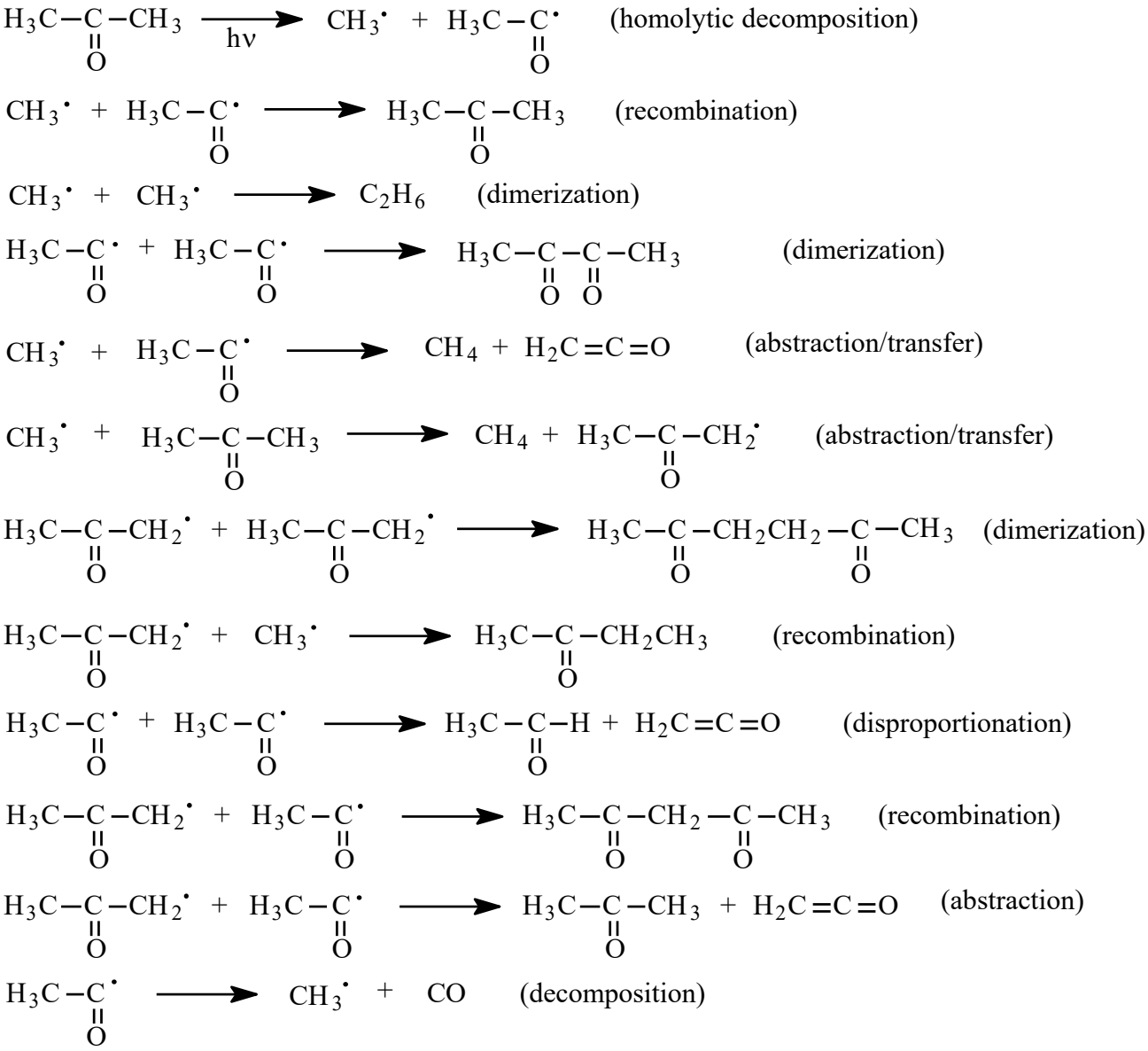








A Typical Radical Reaction Mechanism



Main Processes in the Propagation of Radical Reactions

1) Association Processes (bond formation) :

- **Hydrogen abstraction** — $R^{\bullet} + R'\text{-}X \rightarrow R'^{\bullet} + R\text{-}X$
- **Addition to unsaturated systems**
  - *Aliphatic systems* — $R^{\bullet} + R'\text{-}C{=}C\text{-} \rightarrow R\text{-}C(R')\text{-}C\text{-}C^{\bullet}$
  - *Aromatic systems* — $R^{\bullet} + Ar\text{-}Y \rightarrow R\text{-}Ar\text{-}Y^{\bullet}$
- **Displacement** — $R^{\bullet} + R'\text{-}Y \rightarrow Y^{\bullet} + R\text{-}R'$
- **Ligand transfer** — $R^{\bullet} + ML_n \rightarrow R\text{-}L + ML_{n-1}$

2) Electron Transfer Processes

- **E.T. from metal ions and metals** — $R^{\bullet} + M^{(n\pm1)+} \rightarrow R^{(\pm)} + M^{(n)}$
- **E.T. from organic substrates** — $R^{\bullet} + Sub.^{(\pm)} \rightarrow R^{(\pm)} + Sub.$

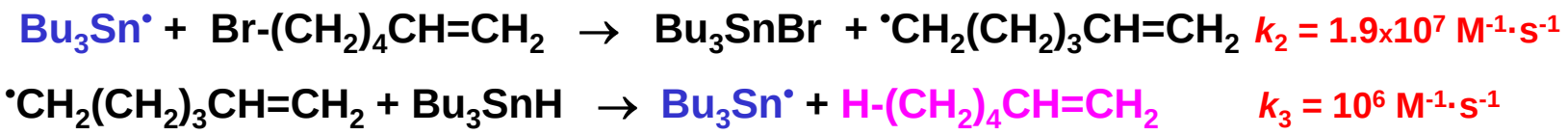
3) Unimolecular Processes

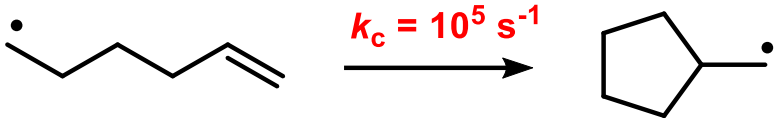
- **Isomerization**
  - *Cyclization* — $\text{-Z=T----X}^{\bullet} \rightarrow \text{-Z(}^{\bullet}\text{)-T----X}$
  - *Intramolecular atom abstraction* — $Y\text{-R-----X}^{\bullet} \rightarrow {}^{\bullet}R\text{-----X-Y}$
- **Decomposition (fragmentation)** — $R^{\bullet} \rightarrow A^{\bullet} + \text{-Z=T-}$

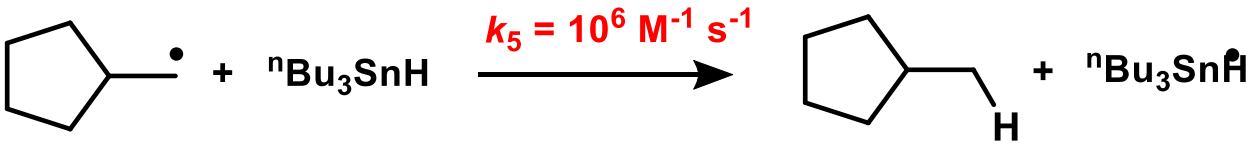
Peculiarity of Radical Chain Reactions
(Relevance of Kinetic Factors)

Initiation

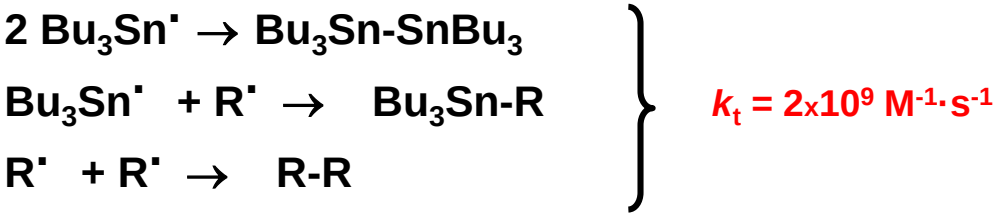
Propagation







Termination



Kinetic of Tin Promoted Radical Chain Reaction

$$\text{Rate} = k_5\,[Bu_3SnH]\,(k_4\,[In]\,/\,k_t)^{1/2}$$

1) Proportional to $[In]^{1/2}$ (slightly sensitive to Initiator concentration)

2) The activation energy is related to the initiation reaction. (E_{att} = 12-18 kcal·mol^{-1}, but for photochemical or radiolytic initiation E_{att} = 0)

3) If rate = 1 M/h, stationary $[R^{\bullet}] = 2.8 \times 10^{-10}$ M

4) Kinetic chain length = 900.000; Mean life time for a chain = 0.9 sec. (rate from [AIBN] = 3×10^{-4} M a 40°C).

- The initiation must be continuous
- All propagation steps must be fast (rate > 10^2) (Importance of kinetic reference data)

5) Quite common competitions between different processes (*k* and [c] control)

Gas Phase Radical Halogenation of Alkanes

$$CH_4 + Cl_2 \xrightarrow{h\nu} CH_3Cl + HCl$$

$$CH_3Cl \xrightarrow{Cl_2} CH_2Cl_2 + HCl$$

$$CH_2Cl_2 \xrightarrow{Cl_2} CHCl_3 + HCl$$

$$CHCl_3 \xrightarrow{Cl_2} CCl_4 + HCl$$

Step 1. initiation: $Cl-Cl \xrightarrow{h\nu} 2\ Cl^{\bullet}$

Step 2. propagation:

(a) $Cl^{\bullet} + H-CH_3 \longrightarrow H-Cl^{\bullet} + CH_3$

(b) $CH_3^{\bullet} + Cl-Cl \longrightarrow ClCH_3 + Cl^{\bullet}$

(c) Repeat (a) and (b)

} Chain reaction

Step 3. Termination:

$Cl^{\bullet} + Cl^{\bullet} \longrightarrow Cl-Cl$

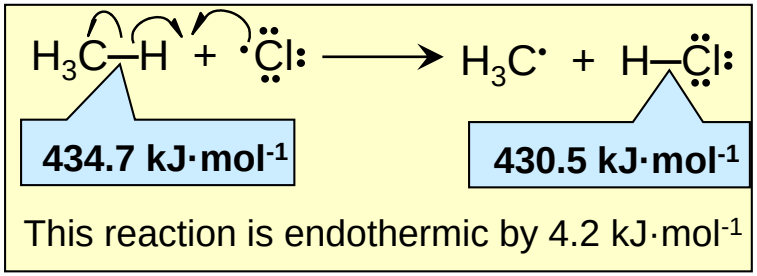
$Cl^{\bullet} + CH_3^{\bullet} \longrightarrow CH_3-Cl$

$H_3C^{\bullet} + CH_3^{\bullet} \longrightarrow H_3C-CH_3$

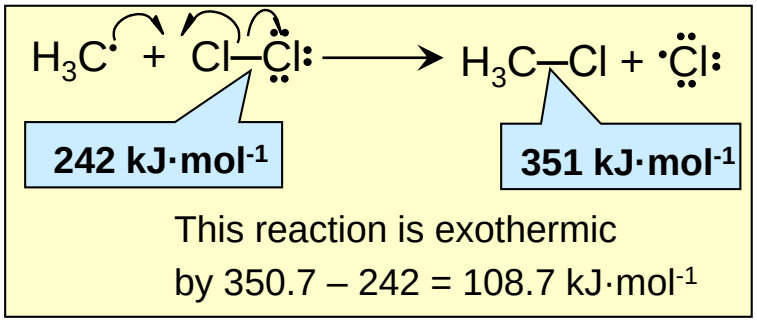
} Possible termination steps

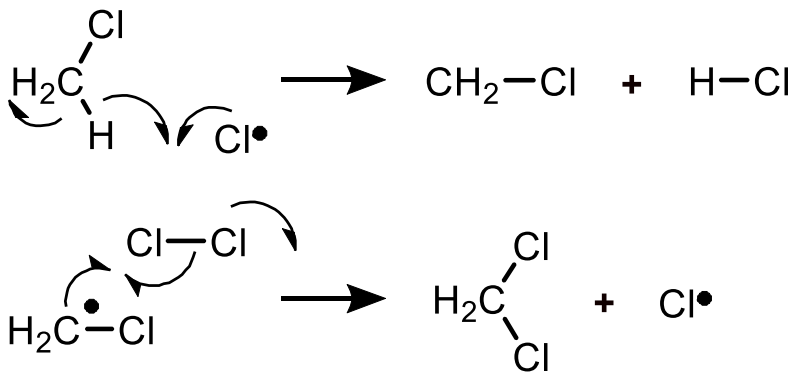
Sequence Reactions

First propagation step



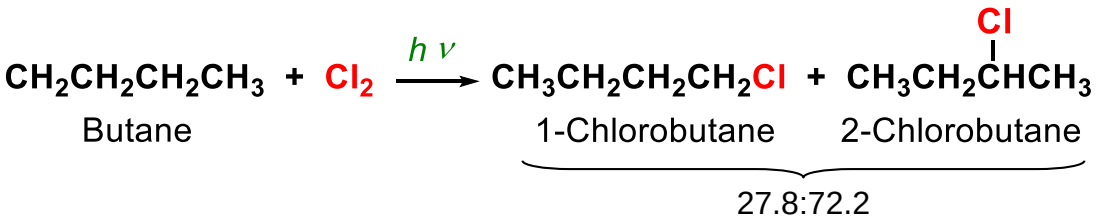
Second propagation step





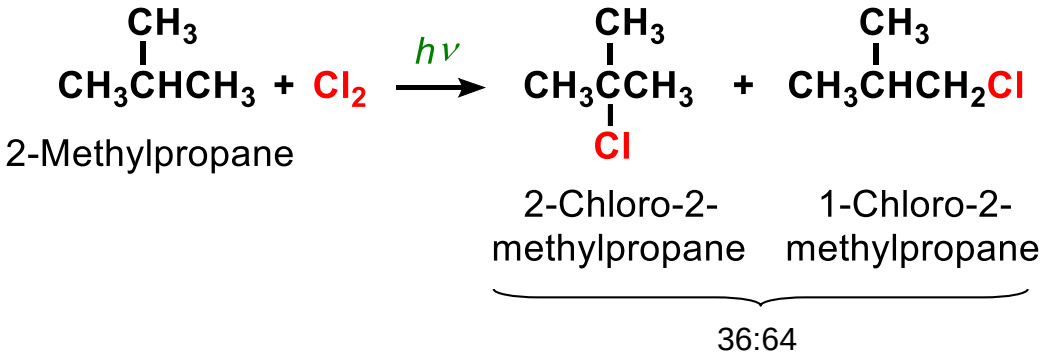
- Increasing the concentration of methyl chloride, the reaction continues, ... until CCl_4 is formed

Selectivity in the H-abstraction



dichloro-, trichloro-, tetrachloro-, and so on

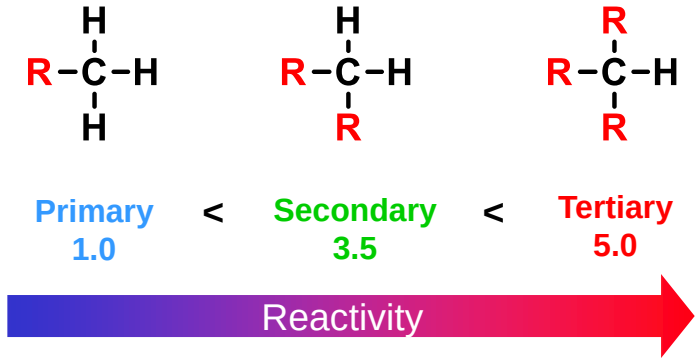
6 primary hydrogen: 27.8% ÷ 6 = 4.63% for Cl• radical
4 secondary hydrogen : 72.2% ÷ 4 = 18.05%
∴ 18.05% ÷ 4.63% = 3.90 (secondary hydrogen/primary hydrogen)



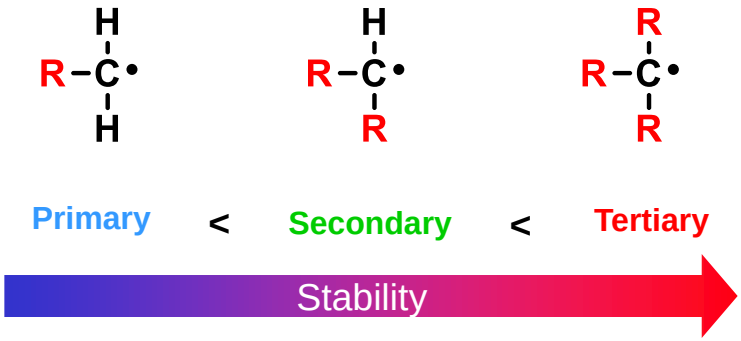
dichloro-, trichloro-, tetrachloro-, and so on

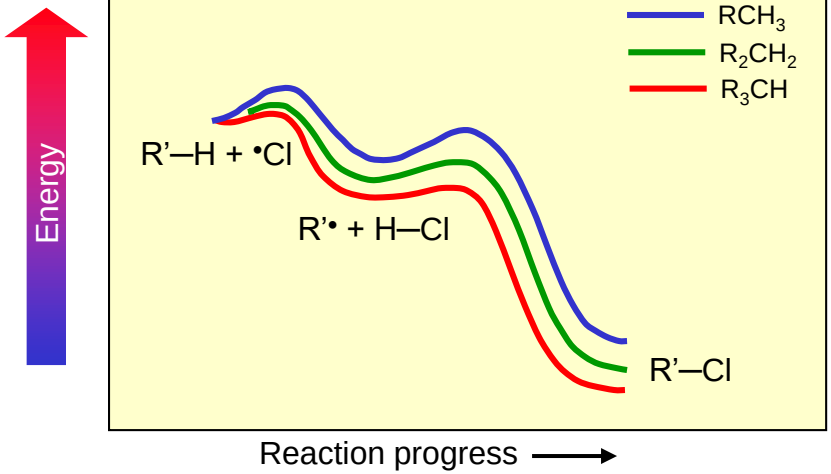
9 primary hydrogen: 64% ÷ 9 = 7.11% for Cl• radical
1 tertiary hydrogen : 36% ÷ 1 = 36%
∴ 36% ÷ 7.11% = 5.06 (tertiary hydrogen/primary hydrogen)

Relationship between Regio-Selectivity and Radical Stability

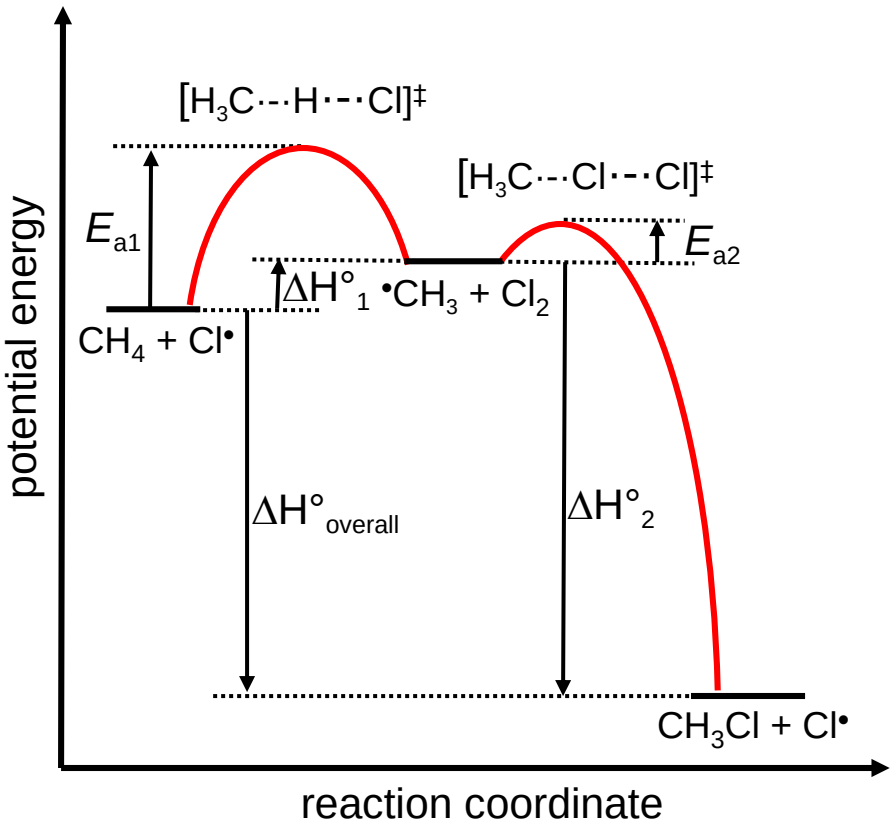


Reactivity		
Primary	C-H ΔH°	= 420 kJ· mol^{-1}
Secondary	C-H ΔH°	= 401 kJ· mol^{-1}
Tertiary	C-H ΔH°	= 390 kJ· mol^{-1}





Drawing the Reaction-Energy Diagram



$$CH_4 + Cl_2 \rightarrow CH_3Cl + Cl$$

From BDEs:

ΔH^0_1 = **+4.2** kJ·mol^{-1}
ΔH^0_2 = **- 108.7** kJ·mol^{-1}
$\Delta H^0_{overall}$ = **-104.5** kJ·mol^{-1}

Experimental Values:
(cannot predict)

E_{a1} = **+16.7** kJ·mol^{-1}
E_{a2} = **+ 4.2** kJ·mol^{-1}

From the diagram, we know:

- The overall reaction is exothermic by 104.5 kJ·mol^{-1}.
- The rate-determining step is step #1.

Reaction of Methane with Other Halogens

- **The order of reactivity of methane substitution with halogens is:**

  fluorine > chlorine > bromine > iodine

- **Fluorination is extremely exothermic therefore fluorination reactions are explosive**
- **Chlorination and bromination reactions less vigorous**
- **Iodinination does not occur**
- **The energy values of the initiation step are unimportant since they occur so rarely**

FLUORINATION

	$\Delta H°$ (kJ·mol^{-1})	E_{act} (kJ·mol^{-1})
Chain Initiation		
$F_2 \rightarrow 2\ F^{\bullet}$	+ 159	+ 159
Chain Propagation		
$F^{\bullet} + CH_4 \rightarrow HF + {}^{\bullet}CH_3$	- 130	+ 5.0
$CH_3^{\bullet} + F_2 \rightarrow CH_3F + F^{\bullet}$	- 302	Small
Overall $\Delta H°$ =	- 432	

Energetic in the Halogenation of Methane

CHLORINATION

	$\Delta H°$ (kJ mol^{-1})	E_{act} (kJ mol^{-1})
Chain Initiation		
$Cl_2 \longrightarrow 2\ Cl^{\bullet}$	+ 243	+ 243
Chain Propagation		
$Cl^{\bullet} + CH_4 \longrightarrow HCl + CH_3^{\bullet}$	+ 8	+16
$CH_3^{\bullet} + Cl_2 \longrightarrow CH_3Cl + Cl^{\bullet}$	– 109	Small
Overall $\Delta H°$ =	– 101	

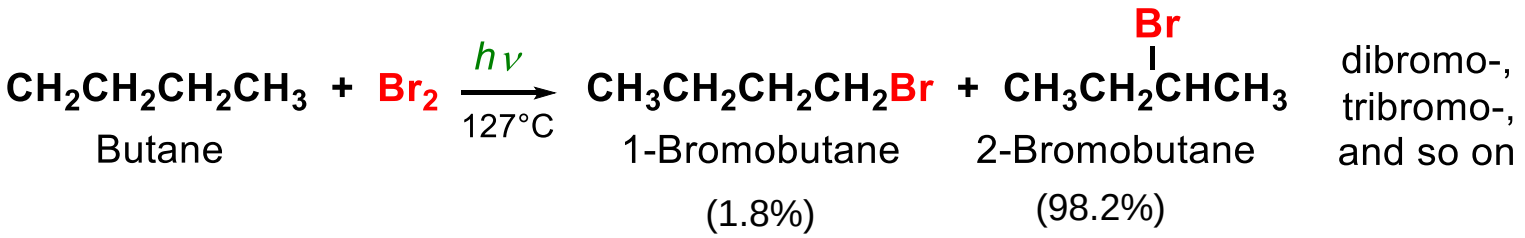
BROMINATION

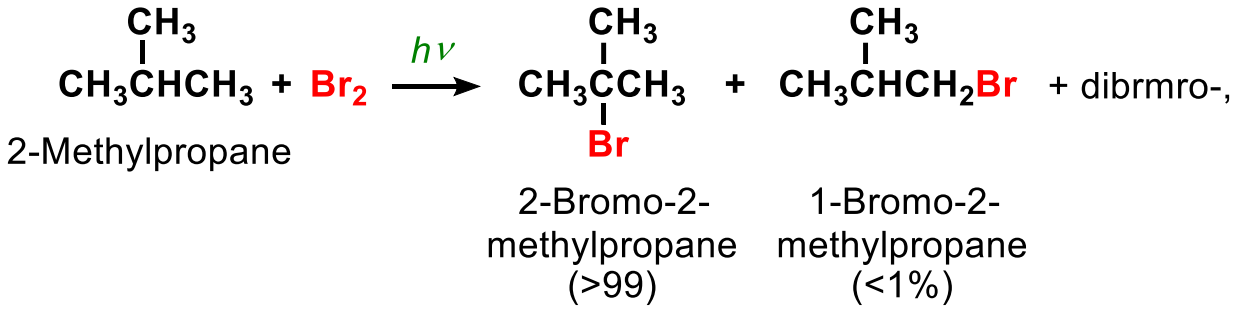
	$\Delta H°$ (kJ mol^{-1})	E_{act} (kJ mol^{-1})
Chain Initiation		
$Br_2 \longrightarrow 2\ Br^{\bullet}$	+ 193	+ 193
Chain Propagation		
$Br^{\bullet} + CH_4 \longrightarrow HBr + CH_3^{\bullet}$	+ 74	+78
$CH_3^{\bullet} + Br_2 \longrightarrow CH_3Br + Br^{\bullet}$	– 100	Small
Overall $\Delta H°$ =	– 26	

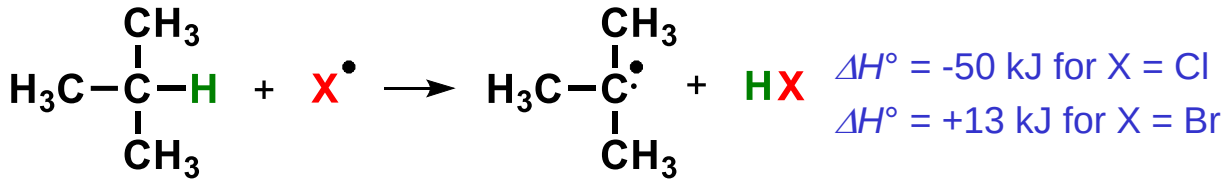
IODINATION

	$\Delta H°$ (kJ mol^{-1})	E_{act} (kJ mol^{-1})
Chain Initiation		
$I_2 \longrightarrow 2\ I^{\bullet}$	+ 151	+ 151
Chain Propagation		
$I^{\bullet} + CH_4 \longrightarrow HI + CH_3^{\bullet}$	+ 142	+140
$CH_3^{\bullet} + I_2 \longrightarrow CH_3I + I^{\bullet}$	– 89	Small
Overall $\Delta H°$ =	+ 53	

Role of the Radical Specie on Selectivity



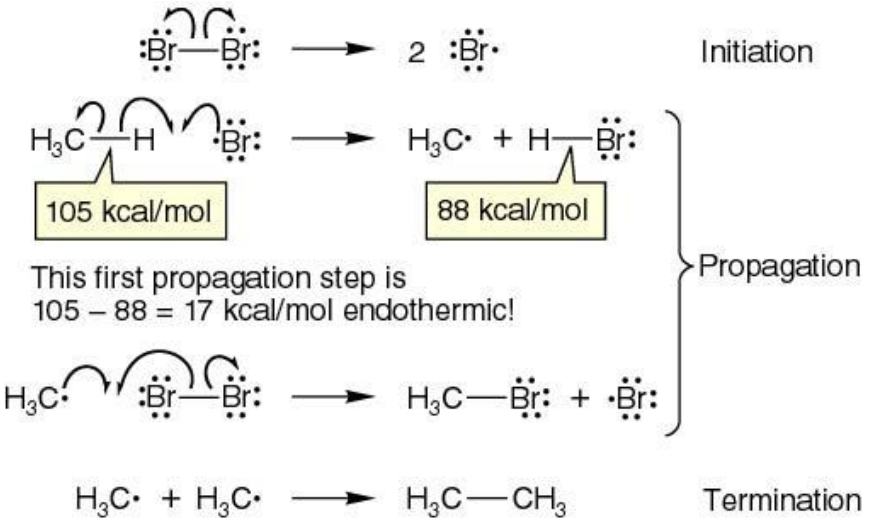




With Br_2 the reaction is much more selective!

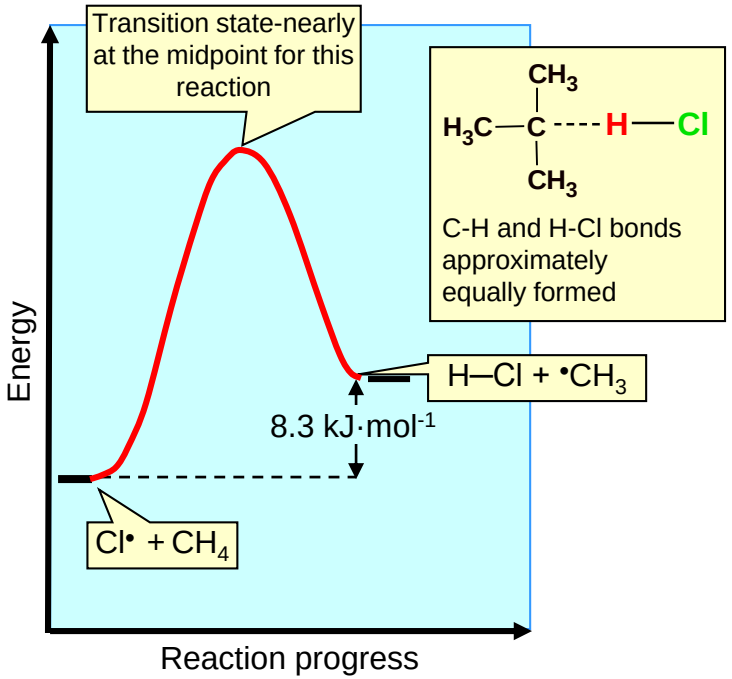
Radical Halogenation with Br_2

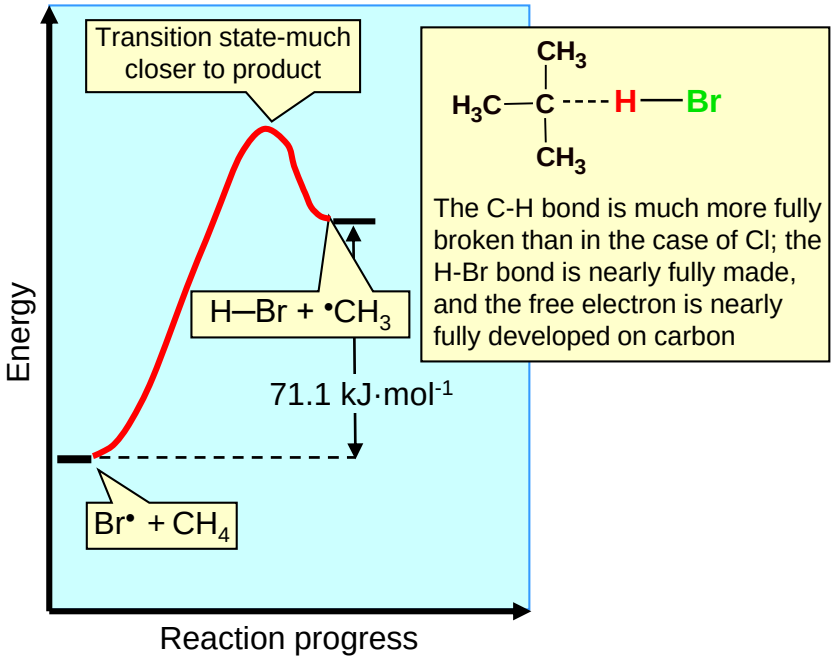
- With bromine, the first step is much more endothermic; this has important consequences for the selectivity.



BDE's (in kcal·mol^{-1})		Selectivity	$^2H_{rxn}$ (kcal·mol^{-1})
Primary C-H: 100.5			
Tertiary C-H: 95 .2			
Cl-Cl: 58.0	$Cl_2/h\nu$	Primary: 64%	- 28.9
H-Cl: 103.2		Tertiary: 36%	-33.0
Primary C-Cl: 84.2			
Tertiary C-Cl: 83.0			
Br-Br 46 .0	$Br_2/h\nu$	Primary: 2%	-11.3
H-Br: 87.5		Tertiary: 98%	-15.6
Primary C-Br: 70 .3			
Tertiary C-Br: 69.3			

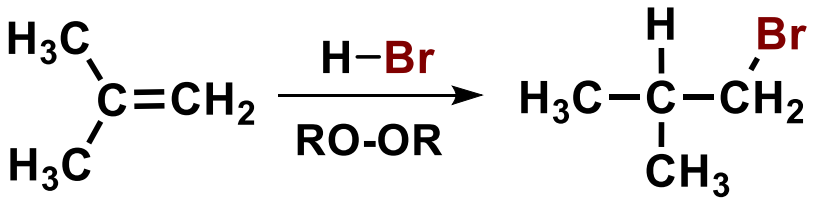
Explanation



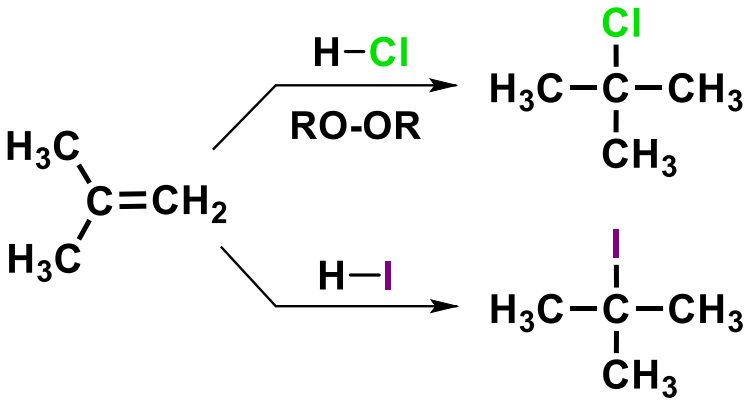


- In the case of Br_2, the transition state for the first step closely resembles the intermediate radical; therefore the stability of the radical plays a more prominent role in the outcome of the reaction

HBr Free Radical Addition to Olefins



- The anti-Markovnikov product is the result of a radical addition of HBr



Always Markovnikov,

Always Markovnikov,

Differences Between Halogens

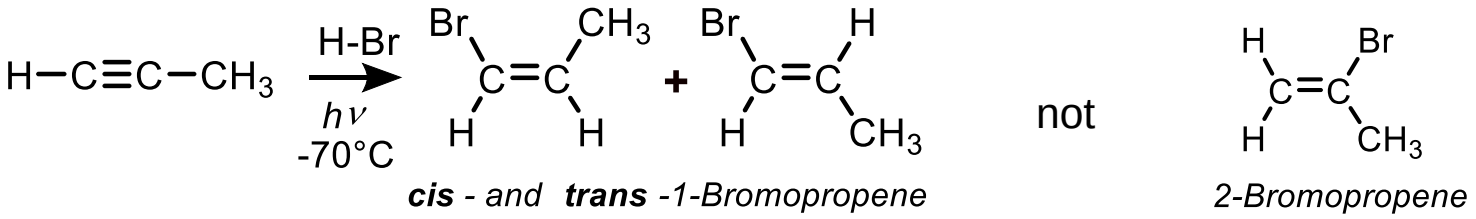
$$X^{\bullet} + H_2C{=}CH_2 \rightarrow X\text{-}CH_2CH_2^{\bullet}$$

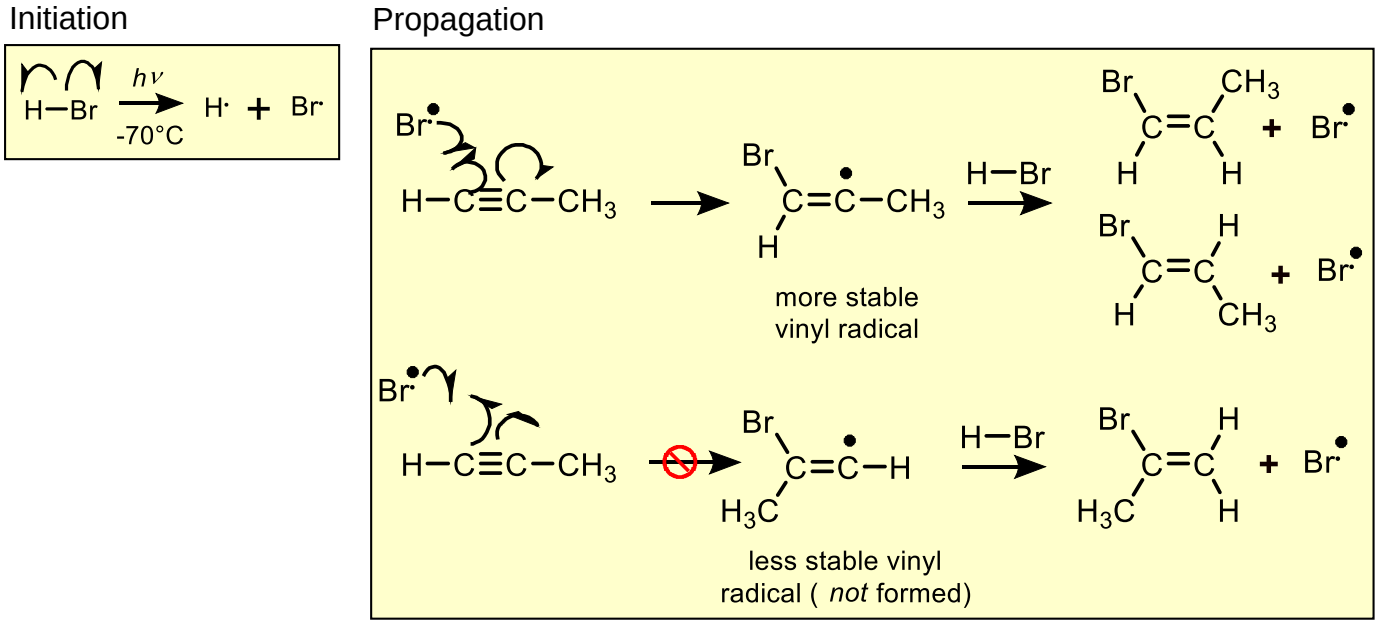
X	Bond Strength (π bond)	Bond Strength (X-C in X-$CH_2CH_2^{\bullet}$)	ΔH (kJ·mol^{-1})
Cl	276	343	-67
Br	276	288	-12
I	276	226	+50

$$H\text{-}X + {}^{\bullet}CH_2\text{-}CH_2X \rightarrow X^{\bullet} + H\text{-}CH_2\text{-}CH_2\text{-}X$$

X	Bond Strength (H-X)	Bond Strength (H-C in H-CH_2CH_2-X)	ΔH (kJ·mol^{-1})
Cl	431	410	+21
Br	364	410	-46
I	297	410	-113

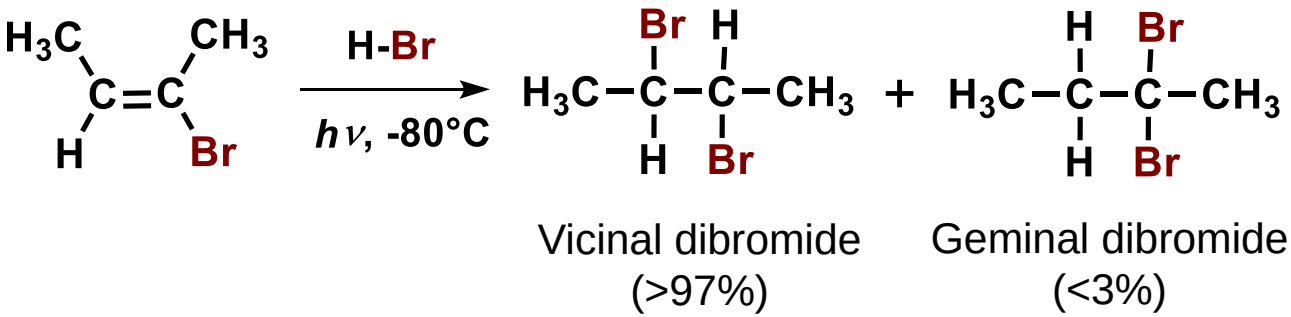
Radical Addition to Alkynes





- Radical addition of HBr to alkynes also gives the anti-Markovnikov product

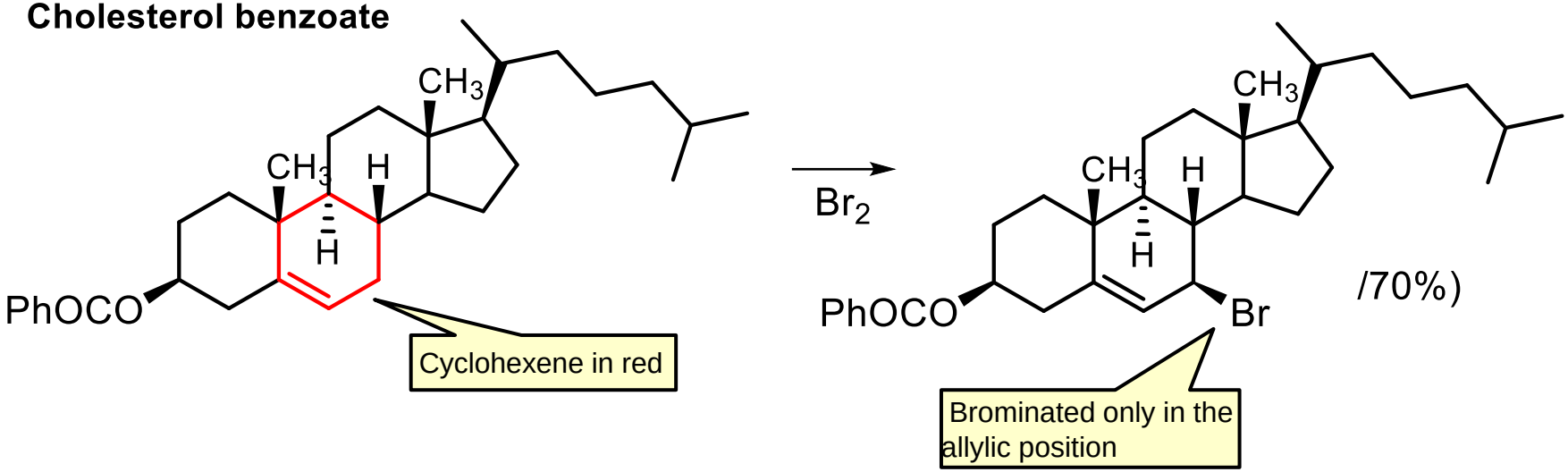
Double Addition Reaction to Alkynes



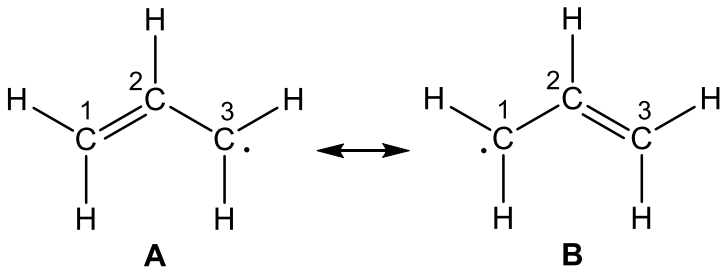
- Repetition of this reaction on several olefins gives always the vicinal dibromide, whereas the ionic reaction gives a geminal dibromide.

Allylic Halogenation

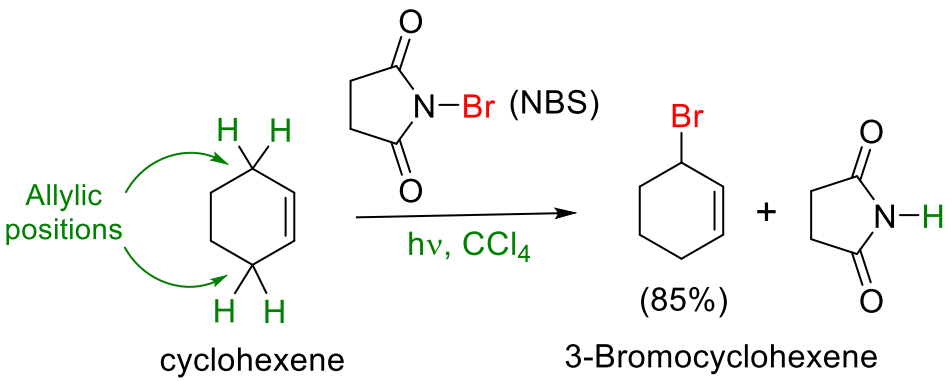
Cholesterol benzoate



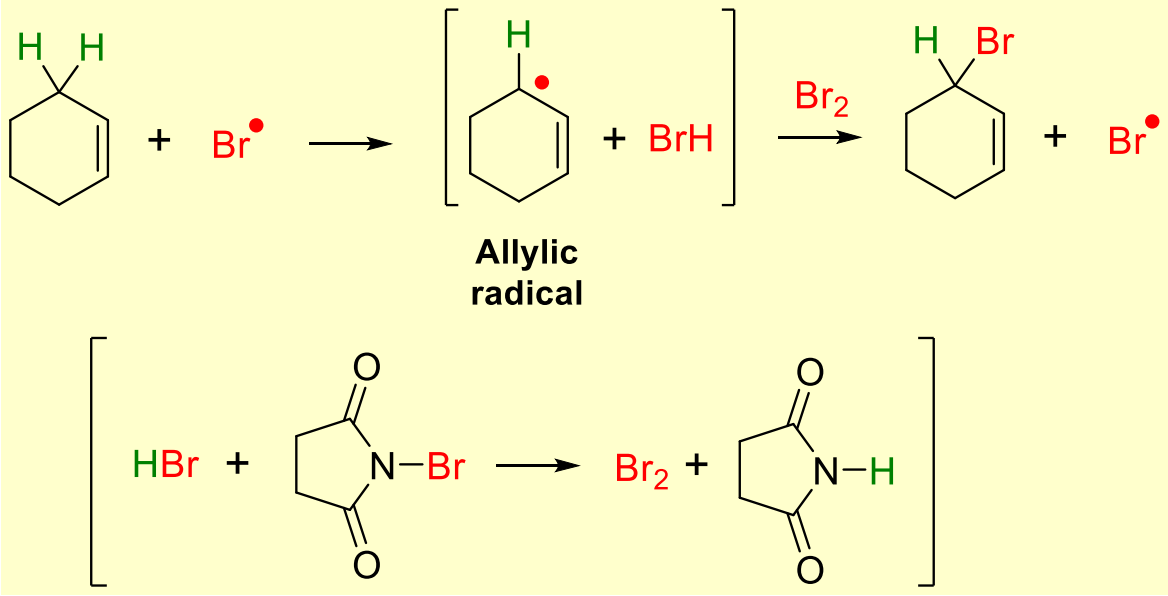
- The allylic position is easily brominated via a radical reaction through a resonant allyl radical.



Allylic Bromination

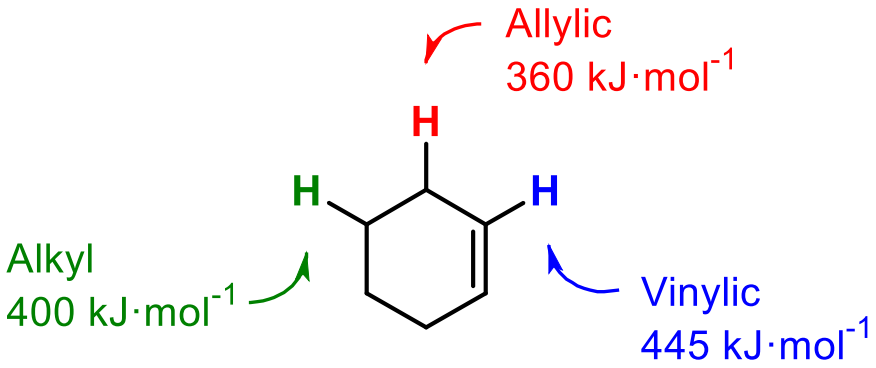


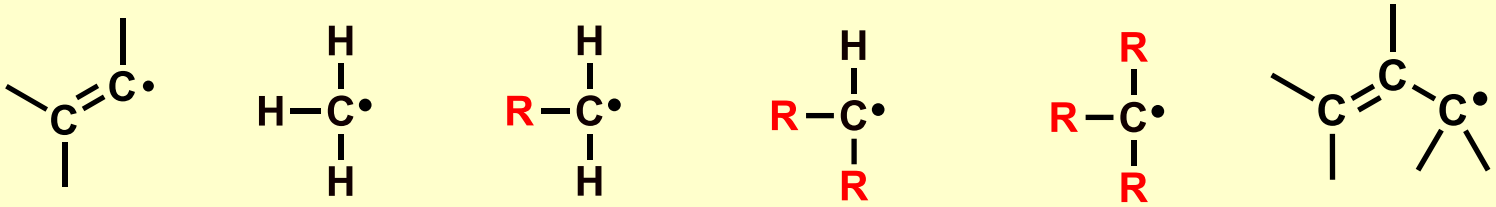
NBS = N-bromosuccinimide



- While NBS is photochemically cleaved to generate the first bromine radical, it also reacts with HBr to form Br_2 which is needed to propagate the chain reaction.

BDE in C-H bonds of Cyclohexene

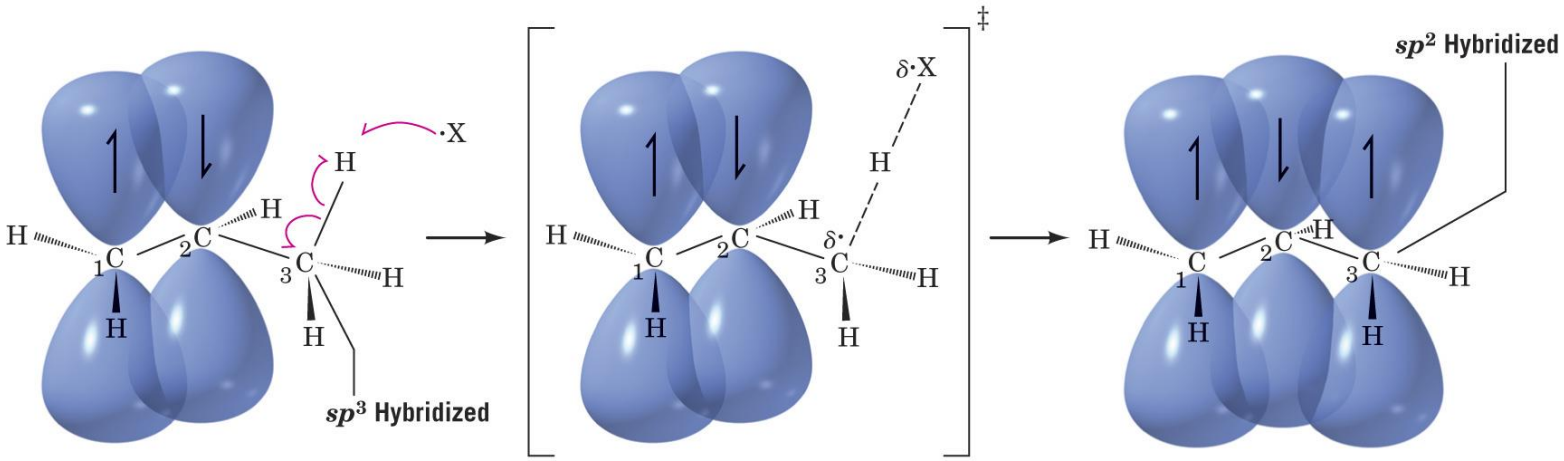




The Stability of the Allyl Radical

When an allylic hydrogen is abstracted to form an allyl radical, the developing *p* orbital on the sp^2 carbon overlaps with the *p* orbitals of the alkene

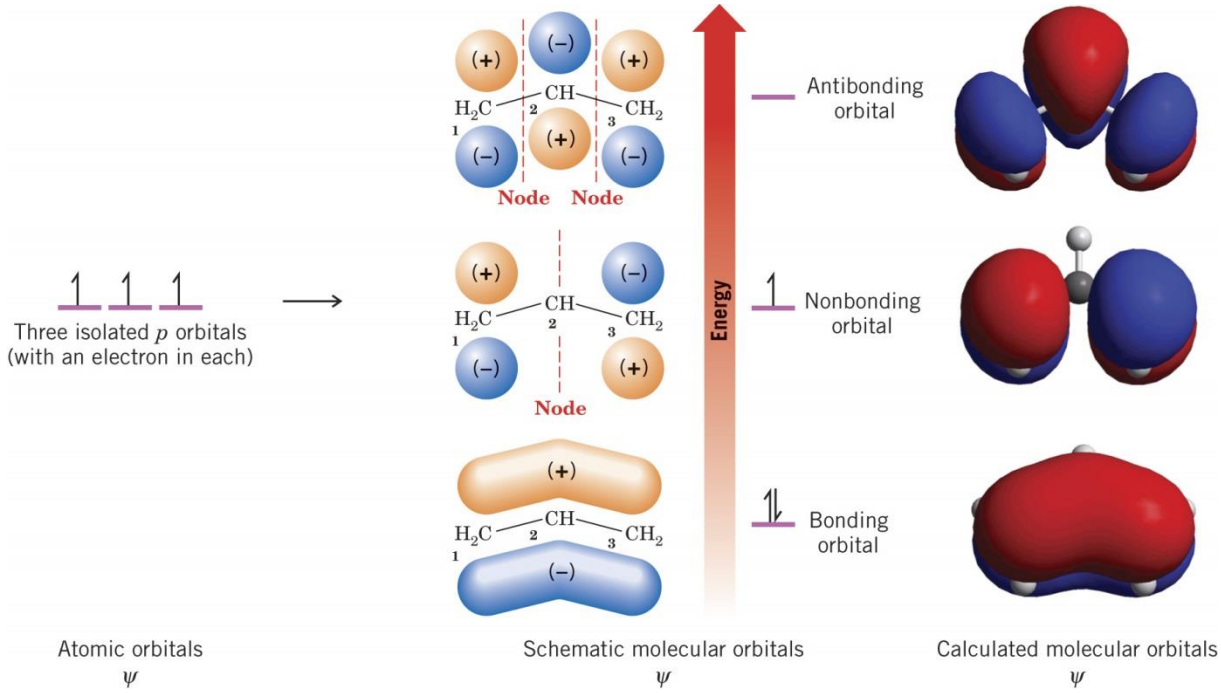
- The new *p* orbital is conjugated with the double bond π orbitals
- The radical electron and the π electrons of the alkene are delocalized over the entire conjugated system
- Delocalization of charge and electron density leads to increased stability

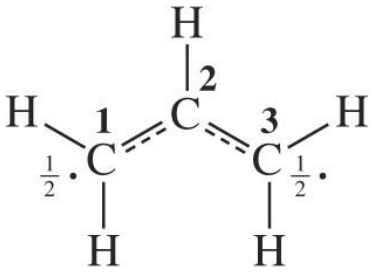


Resonance in Allyl Radical

The three *p* orbitals of the allylic system combine to form three molecular orbitals

- The bonding molecular orbital contains two spin-paired electrons and this orbital increases bonding between the carbons
- The nonbonding orbital contains a lone electron which is located at carbons 1 and 3 only

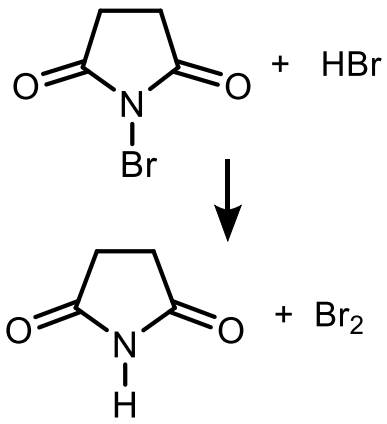


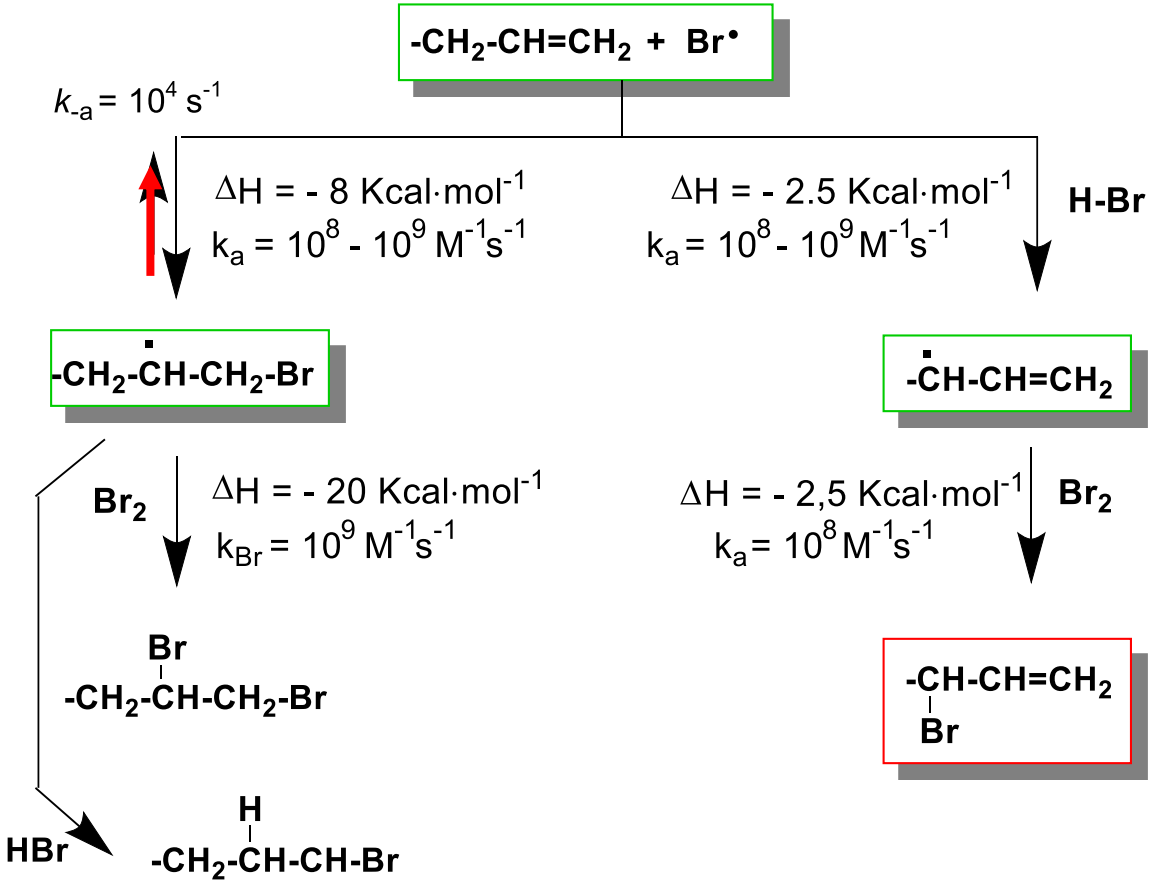


Importance of Kinetic Parameters in Radical Reactions (Reversibility and Selectivity)

Allylic Bromination

Allylic bromination occurs also at low temp. If an effective system of generation di of Bromine atoms, which prevent accumulation of Br_2 or HBr in the reaction medium.
(es. N-bromoamide)

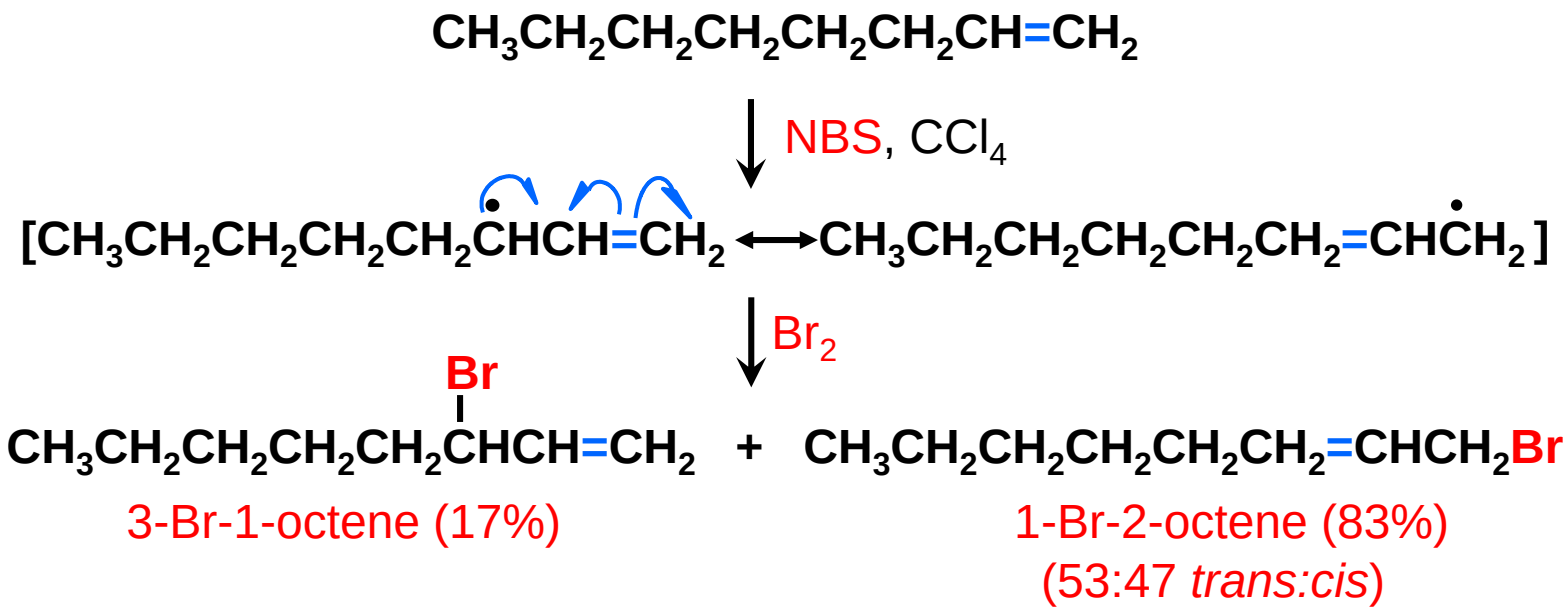




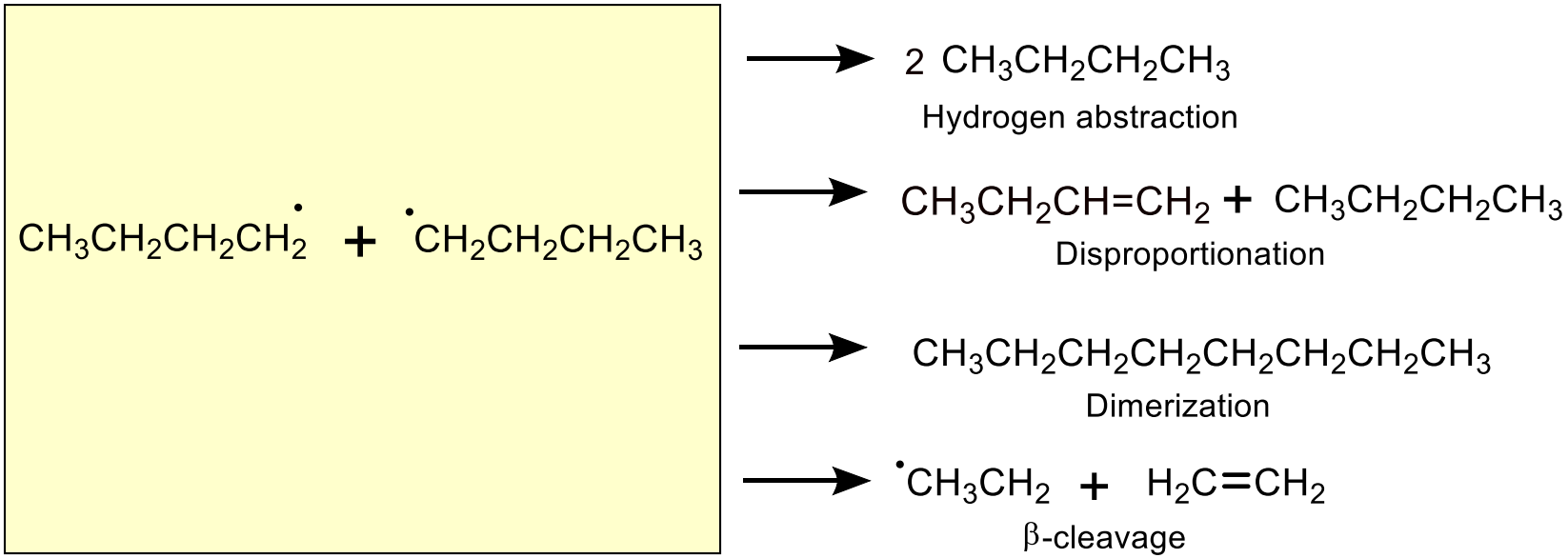
Allylic chlorination occurs only at high temp. owing to the less favorable dissociation equilibrium of β-chloroalkyl radical to Chlorine radical.

Regioselectivity of the Allylic Bromination

Two products are formed in the bromination of unsymmetrical alkenes, i.e. 1-octene, but, because the intermediate allylic radical is not symmetrical and the reaction at the two ends is not equally likely, the substitution at the less hindered, primary end is favored.

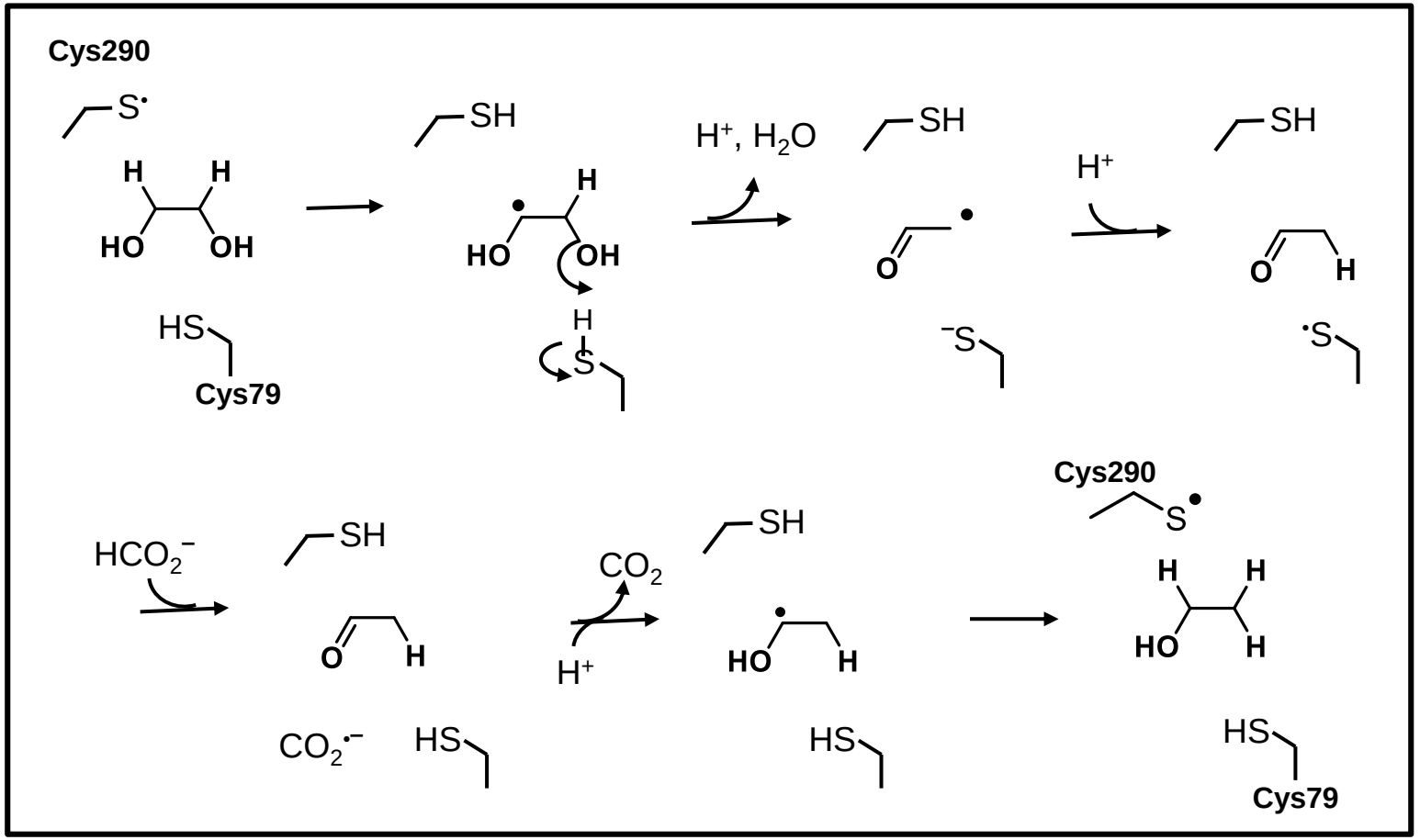


Reactions of Radicals



- These are the most important types of reactions that radicals can undergo.

Complex Hydrogen Transfer Reactions in Biological Systems



Numbering refers to phage T4 NrdD.

RADICAL SOURCES

Sources of Paramagnetic Species

A) THERMAL (breaking of weak bonds)

$$R\text{-}R \xrightarrow{\Delta} 2\ R^{\bullet}$$

(i.e. $^{t}BuO\text{-}OBu^{t} \rightarrow 2\ {}^{t}BuO^{\bullet}$)

B) PHOTOCHEMICAL/RADIOLYTIC (radiation/matter interaction)

$$R\text{-}X \xrightarrow{h\nu} [\ R\text{-}X\ ]^{*} \rightarrow R^{\bullet} + X^{\bullet} \qquad R\text{-}X \xrightarrow{\gamma\ ray} R^{\bullet} + X^{\bullet}$$

(i.e. $CH_3\text{-}I \xrightarrow{h\nu} [CH_3\text{-}I]^{*} \rightarrow CH_3^{\bullet} + I^{\bullet}$)

C) REDOX (redox couples with mono-electron transfer)

$$Red. + X\text{-}Y(ox) \rightarrow Ox. + X^{\bullet} + Y^{-}$$

$$Ox. + X\text{-}H(red) \rightarrow Red. + X^{\bullet} + H^{+}$$

(i.e. $Fe^{2+} + {}^{t}BuO\text{-}OH \rightarrow FeOH^{2+} + {}^{t}BuO^{\bullet}$

$Mn(OAc)_3 + CH_2(CO_2Et)_2 \rightarrow Mn(OAc)_2 + {}^{\bullet}CH(CO_2Et)_2 + AcOH$)

Generation of Free Radicals: Examples of Thermolysis and Photolysis Sources

a) $C_6H_5-C(=O)-O-O-C(=O)-C_6H_5 \xrightarrow[80-100°C]{} 2\ C_6H_5-C(=O)-O^{\bullet} \longrightarrow 2\ C_6H_5^{\bullet} + 2\ CO_2\uparrow$

b) $(CH_3)_2C(CN)-N=N-C(CN)(CH_3)_2 \xrightarrow[80-100°C]{} 2\ (CH_3)_2C^{\bullet}(CN) + N_2\uparrow$

c) $(CH_3)_3C-O-O-C(CH_3)_3 \xrightarrow[140-150°C]{} 2\ (CH_3)_3C-O^{\bullet}$

d) $(R-C(=O)-O-)_4Pb \xrightarrow[140-150°C]{} (R-C(=O)-O-)_2Pb + 2\ R-C(=O)-O^{\bullet}$

e) $RONO_2 \xrightarrow[200°C]{} RO^{\bullet} + NO_2\uparrow$

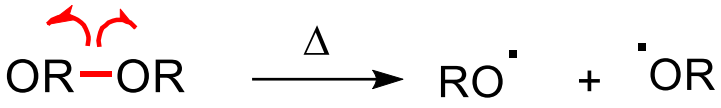
f) $2\ RMgX + CoCl_2 \longrightarrow R_2Co \xrightarrow[35°C]{} 2\ R^{\bullet} + Co$

a) $CH_3-C(=O)-C(=O)-CH_3 \xrightarrow{h\nu} 2\ CH_3-C^{\bullet}(=O)$

b) $CH_3-C(=O)-CH_2Cl \xrightarrow{h\nu} CH_3-C(=O)-CH_2^{\bullet} + Cl^{\bullet}$

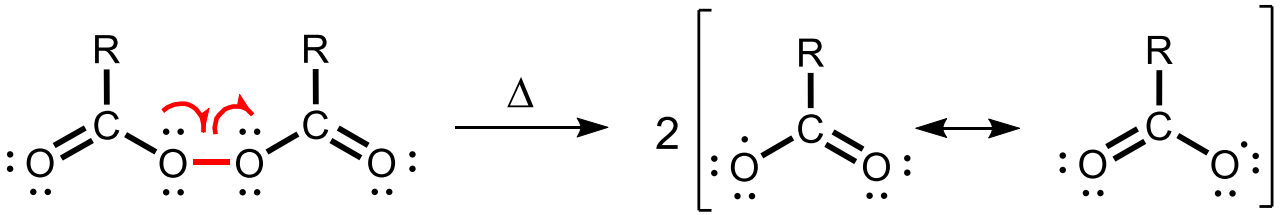
- Thermolysis
- Photolysis

Radical Generation - Weak Bonds: Peroxides



peroxide

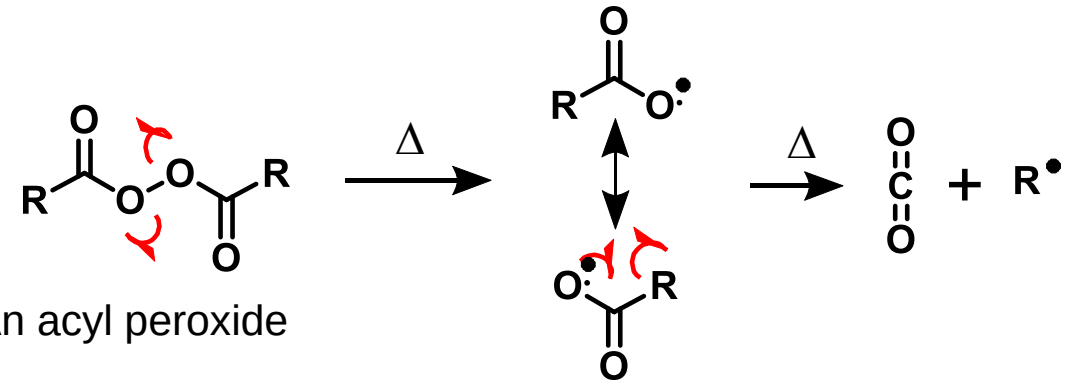
Bond Dissociation Energy (kJ·mol^{-1})
~159



an acyl peroxide

a carboxyl radical

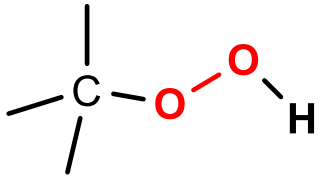
~121



An acyl peroxide

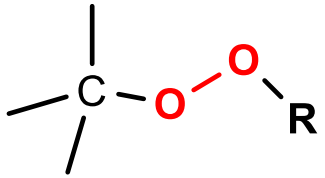
Peroxy Initiators

High temperature initiators:



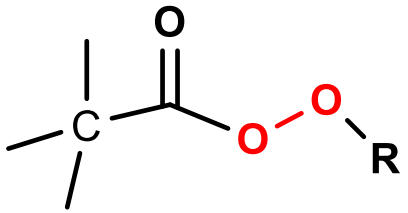
Hydroperoxides

T_d = 155-175°C



Dialkyl Peroxides

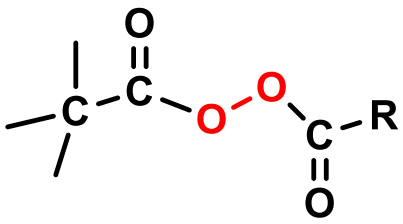
100-135°C



Peresters

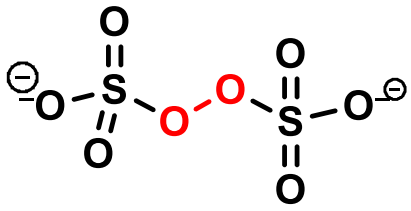
110-130°C

Moderate temperature initiators:



Diacyl Peroxides

T_d = 35-80°C

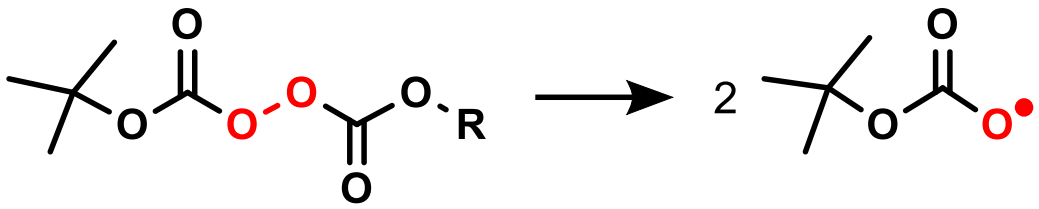


Persulfates

50-90°C

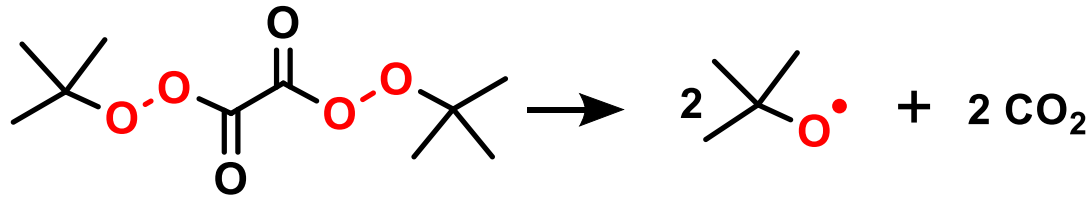
Peroxy Initiators

Low temperature initiators, 35-60 °C



Peroxycarbonates

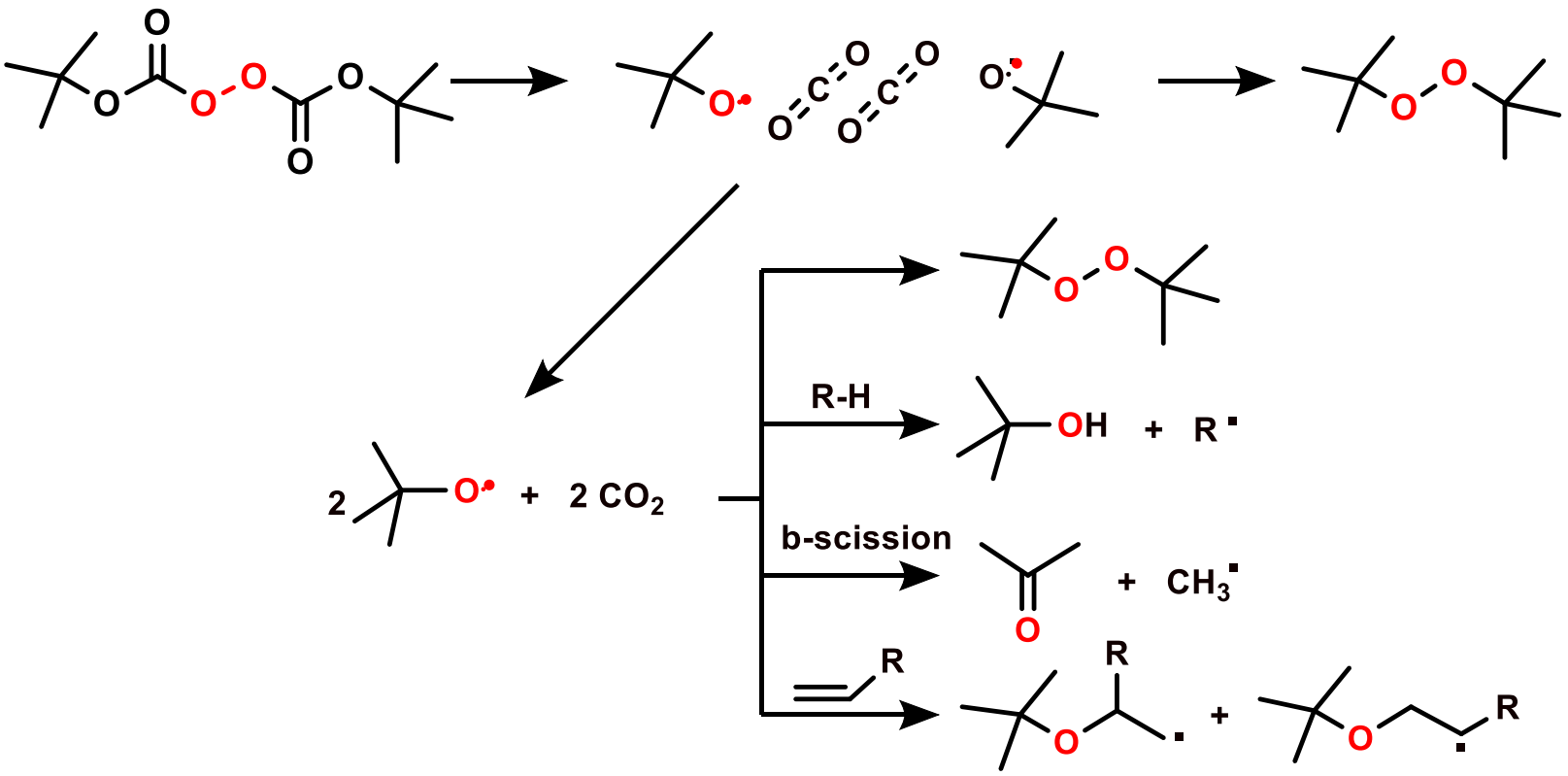
3-bond cleavage process?



Di-t-butyl peroxalate, DBPOX

β-cleavage to carbon centered radical

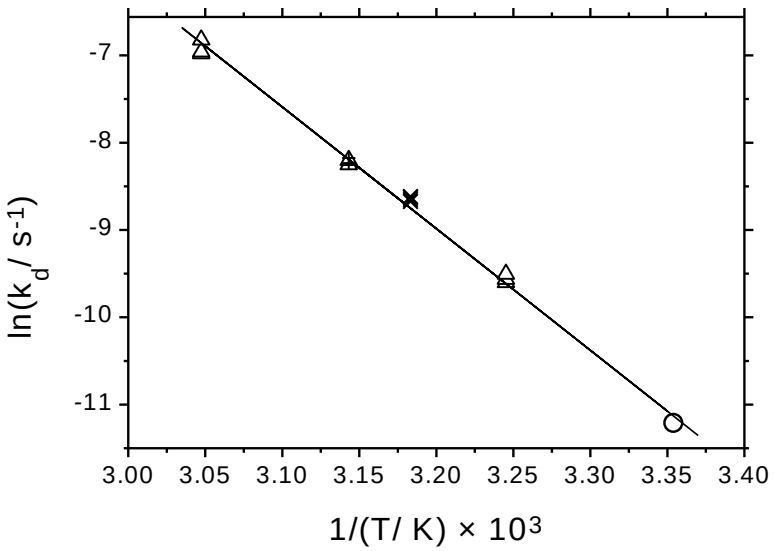
Di-tert-butylperoxalate as Free-Radical Source



Rate Coefficient of Dissociation (k_d)

- Values at 298 K taken from relative trapping experiments

$$k_d = 2.9_1 \times 10^{15}\ s^{-1} \left(\frac{-115._9\ kJ \cdot mol^{-1}}{R\,T} \right)$$



- T = 298 K
- styrene
- two nitroxides
- follow nitroxide consumption

$t_{1/2}$ (298 K) = 13.7 h

Thermolysis of Tert-Butil Perbenzoate

- The rate constant for the thermolysis of *tert*-butyl perbenzoate (R = Ph) is about 10^{-9} s^{-1} at 60°C. This is about 50 times faster than the rate constant for the decomposition of di-*tert*-butyl peroxide and about 50 times slower than the rate constant for dibenzoyl peroxide.

  (Rüchardt, C. Fortschr. Chem. Forsch. 1966, 6, 251).

- It seems that the decomposition is a one-bond cleavage. This is based on scrambling of the label in ^{18}O labeled perester.

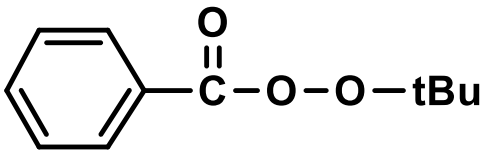
$$^{t}Bu\text{-}O\text{-}OOC\text{-}Ph \rightarrow {}^{t}Bu\text{-}O\bullet + PhCOO\bullet$$

$$PhCOO\bullet \rightarrow Ph\bullet + CO_2$$

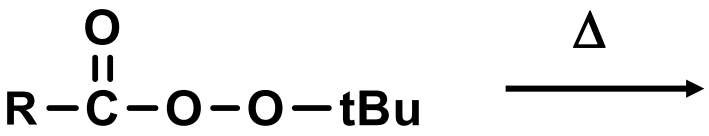
  (Koenig, T. , Deinzer, M., Hoobler, J. A. J. Am. Chem. Soc. 1971, 93, 938)

- The decomposition of *tert*-butyl peracetate is more complicated.

  (Goldstein, M. J. Judson, H. A. J. Amer. Chem. Soc. 1970, 92, 5413.)

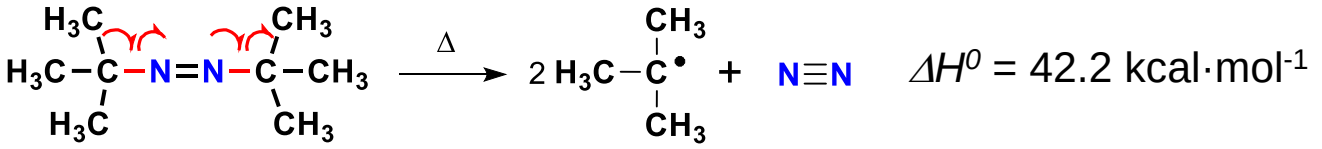


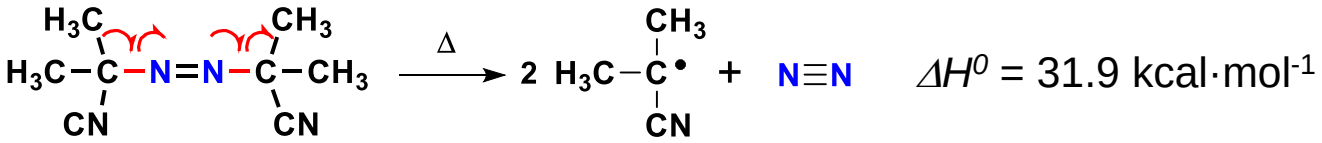
Structure/reactivity Relationships in Radical Forming Reactions



R	$t_{1/2}$	ΔH^* kcal·mol^{-1}	ΔS^* e.u.
CH_3	500,000	38	17
$PhCH_2$	1700	28.7	3,9
t-Bu	300	30.6	13.0
$PhCH{=}CHCH_2$	100	23.5	-5.9
Ph_2CH	26	24.3	-1.0
$Ph(CH_3)_2C$	12	26.0	5.8
$Ph_2(CH_3)\,C$	6	24.7	3.3

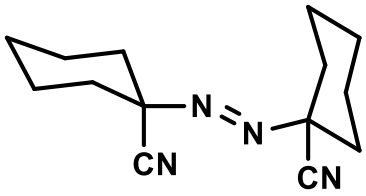
Radical Generation - Weak Bonds: Azo compounds (Diazenes)



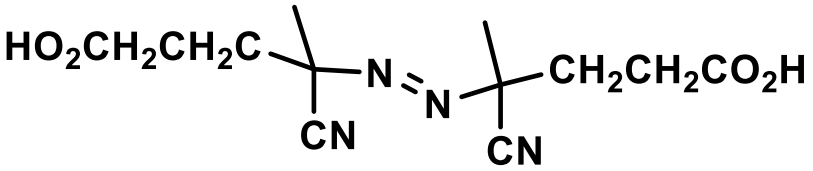


AIBN

- **Start from compounds that readily loose a stable compound such as nitrogen gas (so called azo-compounds)**
- **A widely used radical initiator is AIBN (azobisisobutyronitrile) ...**

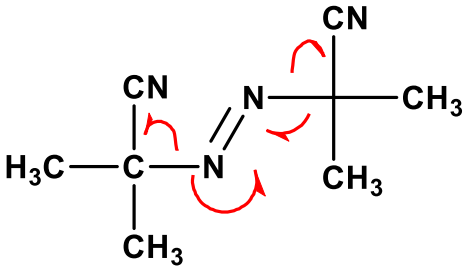


1,1'-azobis(1-cyclohexanenitrile)

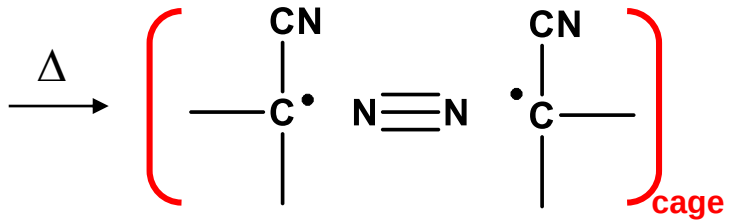


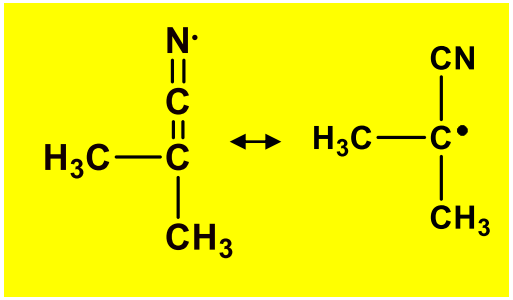
4,4'-azobis(4-cyanovaleric acid)

Efficiency of Thermal Radical Initiation



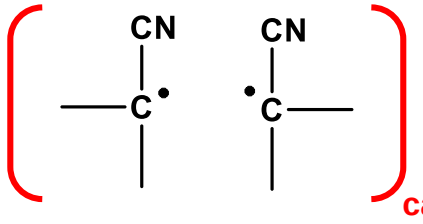
AIBN

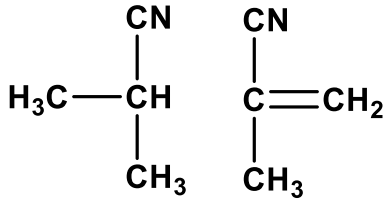




α-Cyanoisopropyl Free Radical

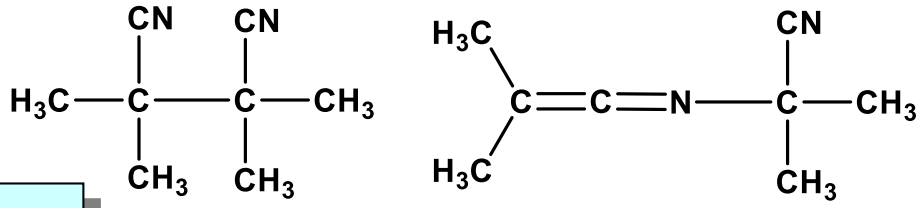
diffusion





disproportionation

dimerization



$$\text{Efficiency} = \frac{\text{Moles of free radical}}{\text{Moles of decomposed initiator}}$$

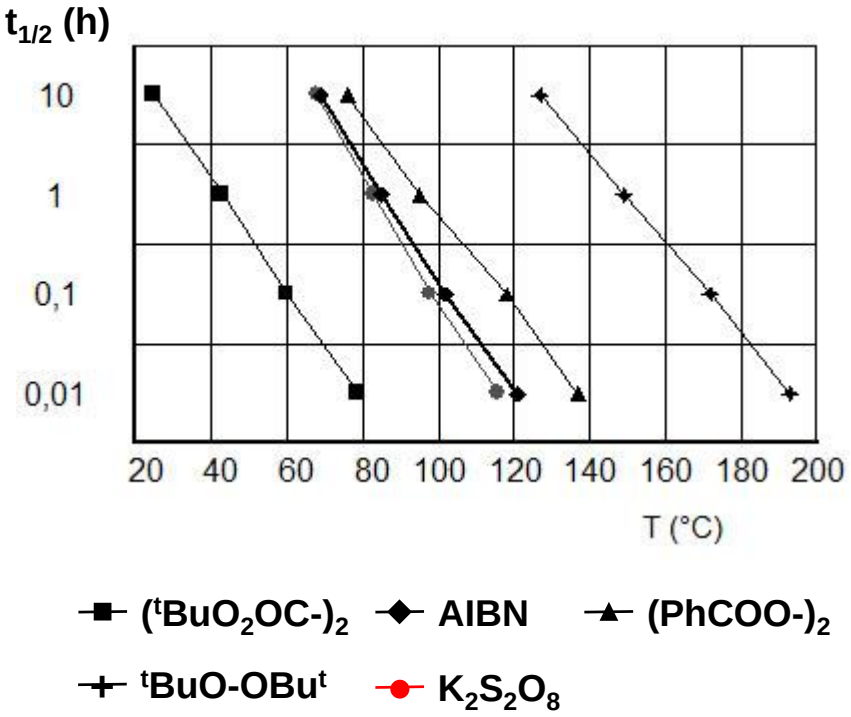
Thermal Radical Sources

Bond Dissociation Energy of typical initiators

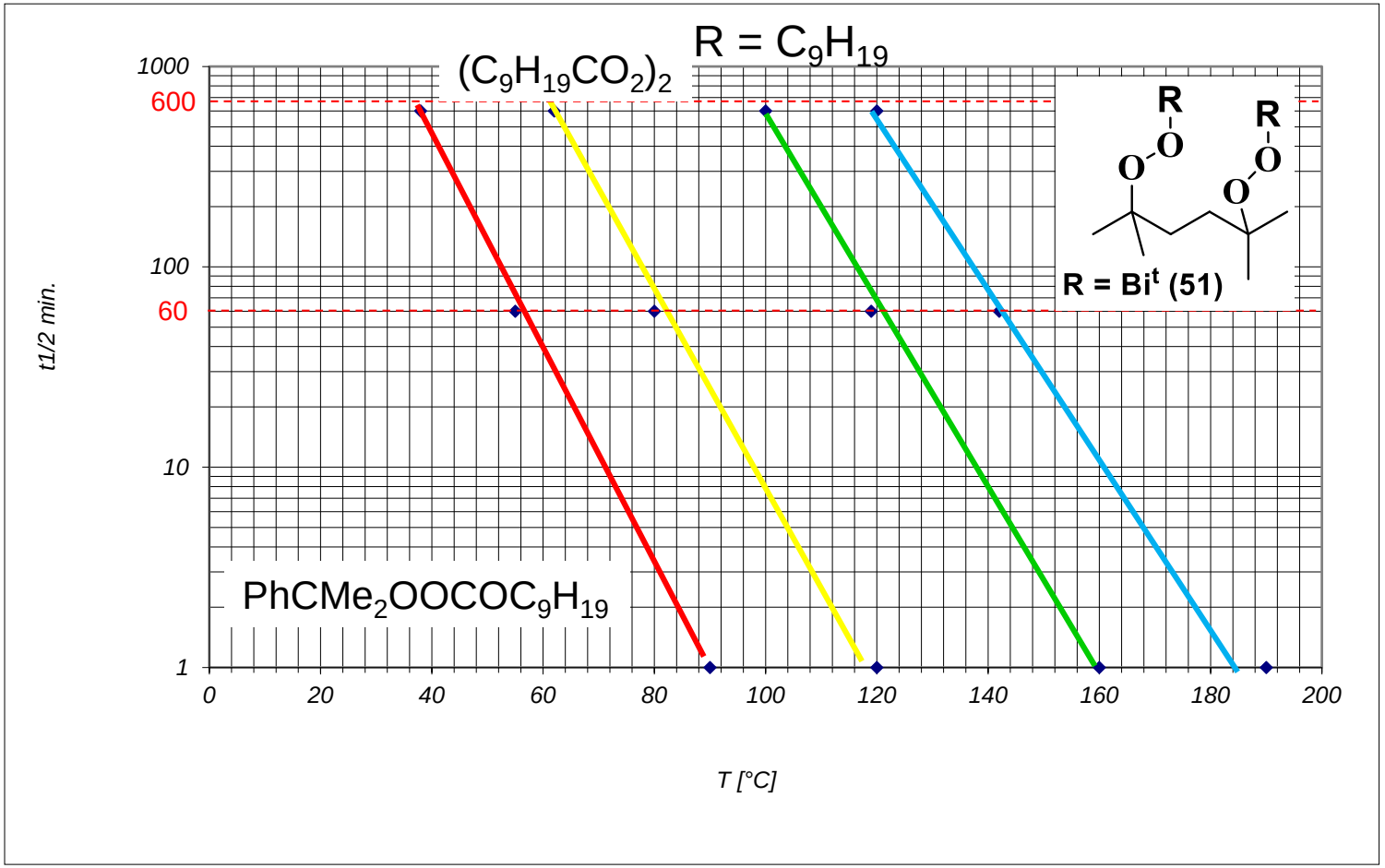
Compound	ΔH_d (kJ·mol^{-1})
HO-OH	213
H_2N-NH_2	242
HO-Cl	251
MeN=N-Me	192
ONO-Me	234
MeHg-Me	217
Cl_3C-Br	205
$(PhC(CH_3)_2\text{-})_2$	259

- **Bonds between electronegative atoms**
- **Bonds in organometallics**
- **Sterically hindered bonds**

Half life for decomposition of typical thermal initiators (approximate values owing to the dependence from solvent)



Half-Life of Some Commercial Peroxides (Storage and Handling)



Generation of Free Radicals: Redox Reactions

a) $RCOO^- \xrightarrow[\text{anode}]{-e^-} RCOO^\bullet \longrightarrow R^\bullet + CO_2\uparrow$ (Kolbe electrolysis)

b) $Ti^{+3} + {}^tBuO_2H \longrightarrow Ti^{+4} + OH^- + {}^\bullet OBu^t$

c) $Fe^{+2} + H_2O_2 \longrightarrow Fe^{3+} + OH^- + {}^\bullet OH$

d) $C_6H_5CH_2Cl \xrightarrow[\text{Na vapor}]{} C_6H_5CH_2^\bullet + NaCl$

e) $(C_6H_5)_3COH \xrightarrow[H^+]{} (C_6H_5)_3C^+ \xrightarrow[V^{+2}]{} (C_6H_5)_3C^\bullet + V^{+3}$

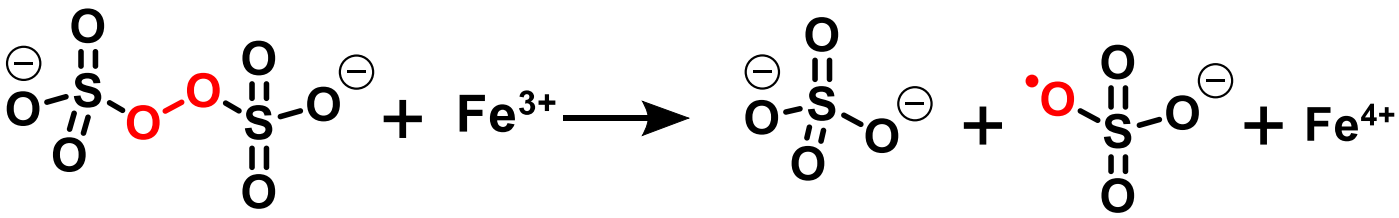
f) $(C_6H_5)_3CH \xrightarrow[NH_2^-]{} (C_6H_5)_3C^- \xrightarrow[Ag^+]{} (C_6H_5)_3C^\bullet + Ag^0$

g) $C_6H_5OCH_3 + Ag^{2+} \longrightarrow C_6H_5O\overset{\bullet}{C}H_3^{+} + Ag^+$

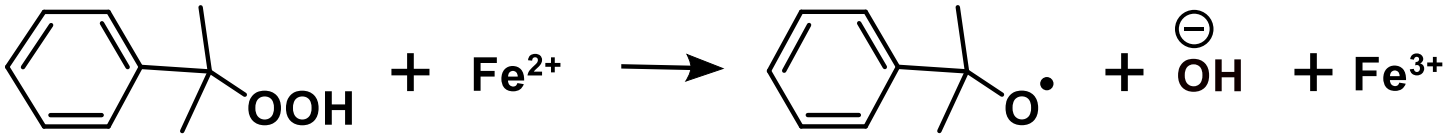
h) $^-OC_6H_4O^- + O_2 \longrightarrow {}^-OC_6H_5O^\bullet + O_2^{\bullet -}$

Redox Initiation

0-5 °C in water



0-5 °C in organic/aqueous phase



cumyl hydroperoxide

Organometallics

C-M bonds have low BDE, and are easily homolyzed into radicals;

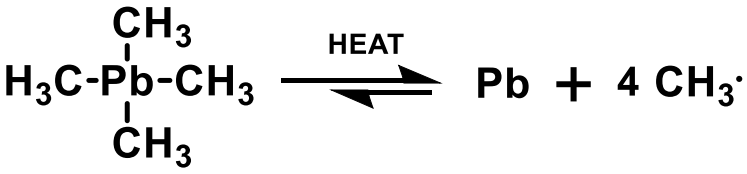
Trialkylboranes:

$R_3B + O_2 \rightarrow R_2BOO^{\bullet} + R^{\bullet}$

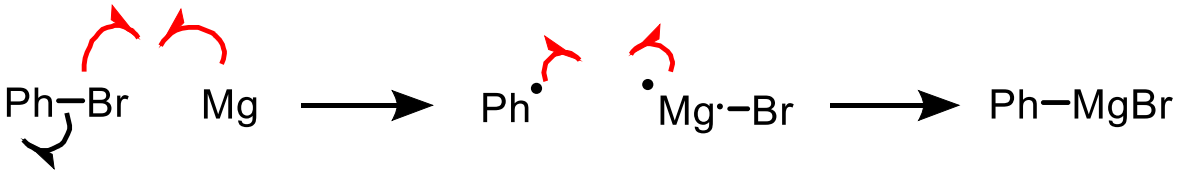
Metal carbonyls:

$Mn_2(CO)_{10} \rightarrow 2\ (CO)_5Mn^{\bullet}$

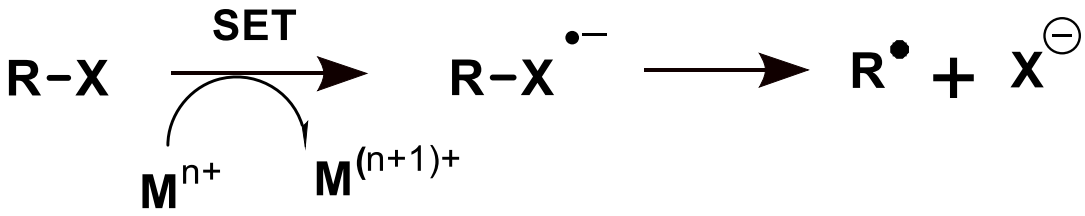
Organo-lead:

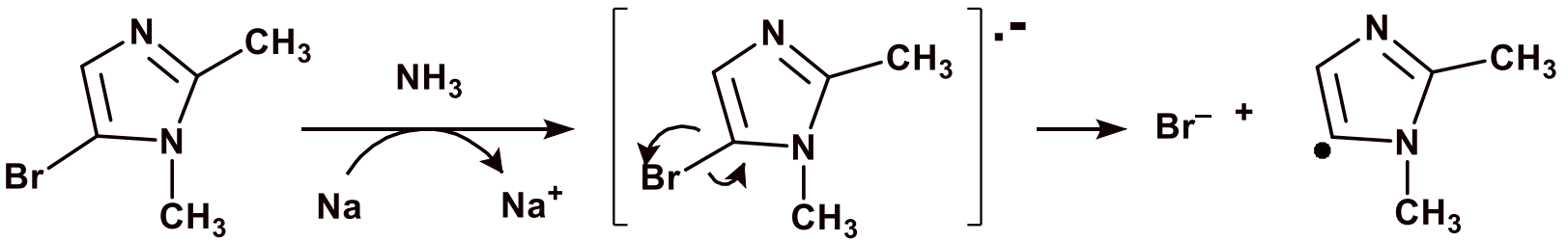


FORMATION OF GRIGNARD REAGENTS:



SET (Single Electron Transfer) Reactions





σ* - radical anion

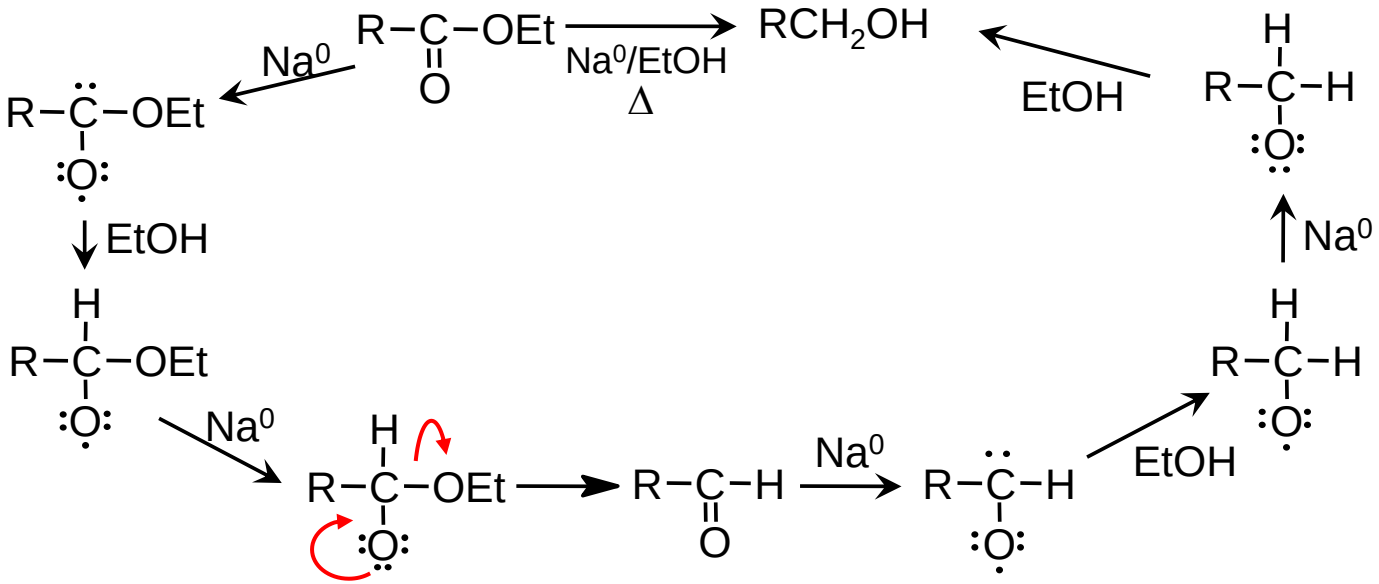
σ - inidazolyl radical

Initiation using a metal in ammonia

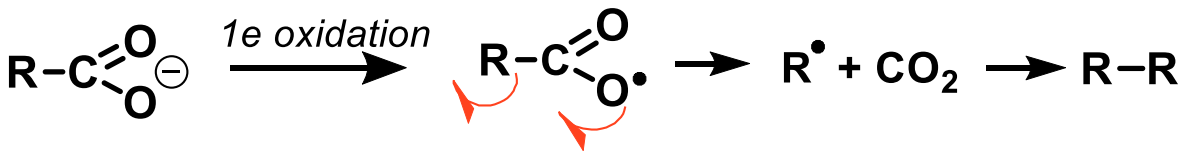
$ArX + e^{-}(NH_3) \longrightarrow (ArX)^{\bullet -}$

Generation of Radicals by Electron Transfer Processes

i) Reduction via carbonyl anion radicals, i.e. Ester Reduction by Na in Ethanol



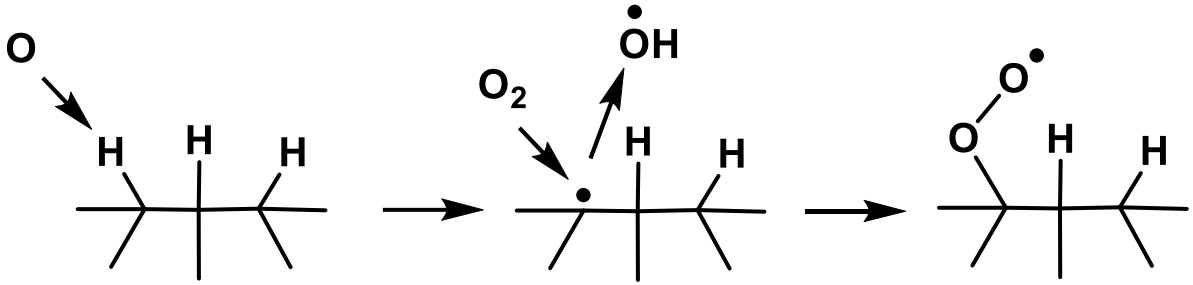
Kolbe Reaction - Electrochemical oxidation

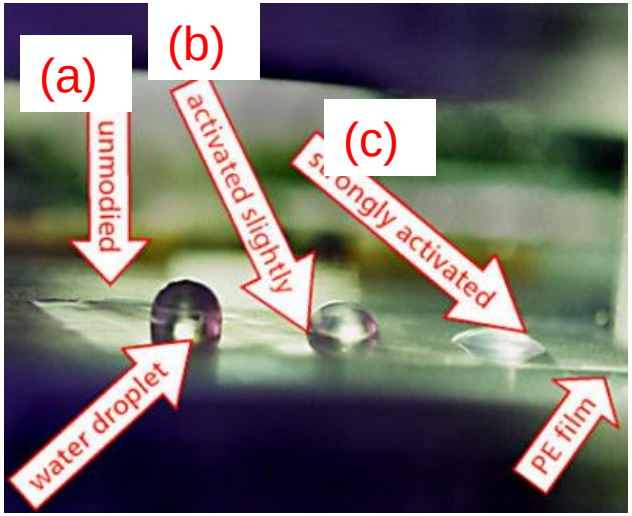


Functionalization of Polymer Surfaces by Plasma Sources

- **Functionalization occurs by the chemical interaction of plasma produced species - ions, radicals and photons with the surface.**

$$e^- + O_2 \rightarrow O + O + e^-$$



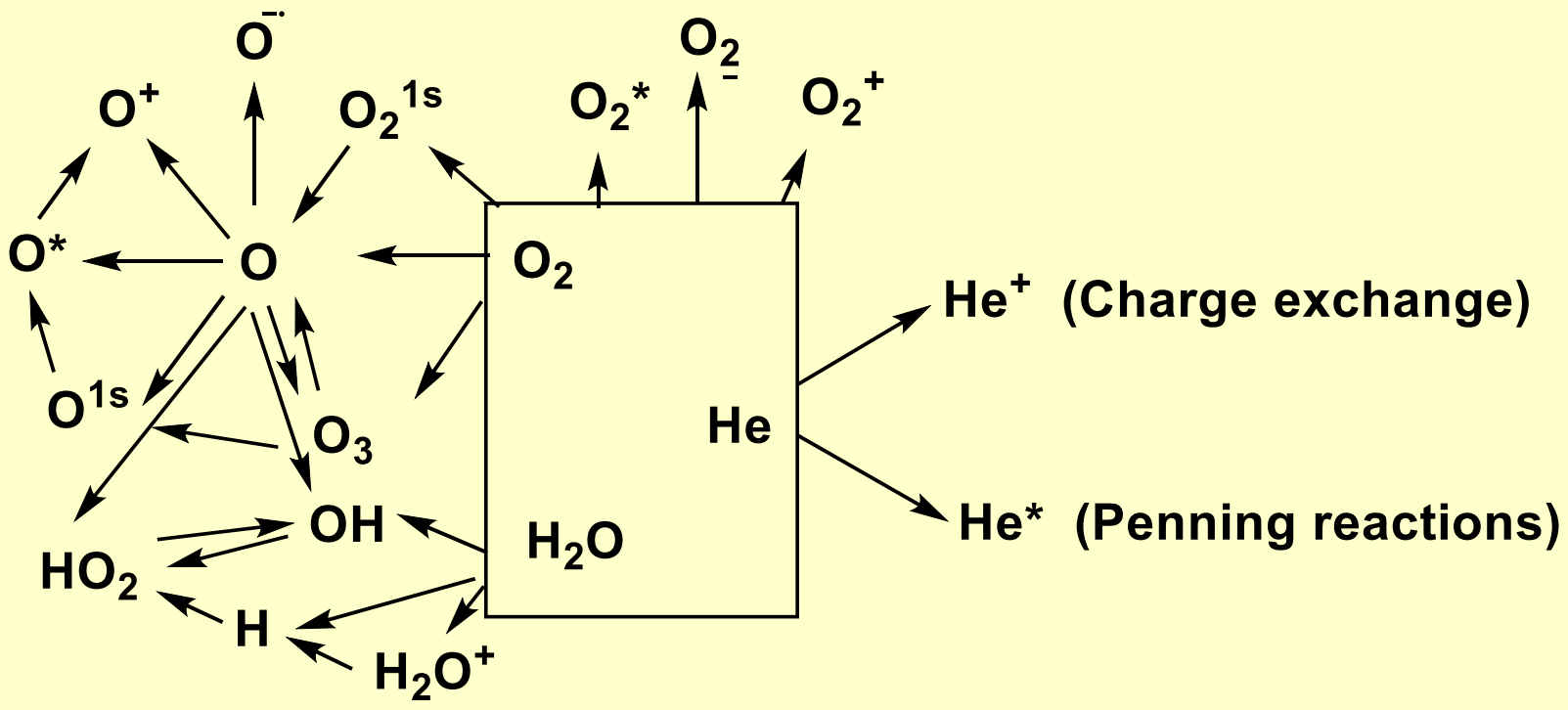


- **Chemical groups are incorporated onto the surface which change surface properties.**
- **Process usually only treats the top mono-layers not affecting the bulk.**

Wettability on PE film with 3 zones of treatment:
a) untreated b) slightly treated c) strongly treated.

Gas Phase Chemistry: $He/O_2/H_2O$

- **Treatment in O_2 containing plasmas is known to effectively incorporate O atoms into the surface.**



- **Process is initiated by electron impact dissociation of O_2 and H_2O into radicals such as O and OH.**