Organic Chemistry III

Mohammad Jafarzadeh Faculty of Chemistry, Razi University



II. Electrocyclic reactions

The Diels-Alder reaction couples the ends of two separate π systems. Can rings be formed by the linkage of the termini of a *single* conjugated di-, tri-, or polyene? Yes

The conversion of 1,3-butadiene into cyclobutene is endothermic because of ring strain. The reverse reaction, ring *opening* of cyclobutene, occurs readily upon heating.

Ring *closure of cis*-1,3,5-hexatriene to 1,3-cyclohexadiene is exothermic and takes place thermally.



 $\Delta H^{\circ} = -14.5 \text{ kcal mol}^{-1} (-60.7 \text{ kJ mol}^{-1})$ Ring closure to six-membered ring is exothermic

 $\Delta H^{\circ} = -9.7 \text{ kcal mol}^{-1} (-40.6 \text{ kJ mol}^{-1})$ Ring opening of four-membered ring is exothermic

Electrocyclic transformations are driven by heat or light

We know that in a thermal reaction this is a difficult task, because equilibrium is governed by thermodynamics. However, the problem can be surmounted in some cases by using light, so-called **photochemical reactions.**

In these, absorption of a photon by the starting material excites the molecule into a higher energy state. Molecules can relax from such excited states to furnish thermodynamically less stable products than starting material(s).

It allows electrocyclic reaction equilibria to be driven in the energetically unfavorable direction.

Irradiation of 1,3-cyclohexadiene with light of appropriate frequency will cause its conversion to its triene isomer. Similarly, irradiation of 1,3-butadiene effects ring closure to cyclobutene.

Exercise 14-25

Give the products obtained on heating the following compounds.



To form the new σ bond in the electrocyclic reaction, the *p* orbitals at the end of the conjugated system must overlap head-to-head.

Only the symmetry of the HOMO is important in determining the course of the reaction.



A **symmetry-allowed** pathway is one in which in-phase orbitals overlap.

If a reaction is **symmetry-forbidden**, it cannot take place by a concerted pathway.

The symmetry of the HOMO of the compound undergoing ring closure **controls** the **stereochemical** outcome of an electrocyclic reaction.

Electrocyclic reactions

The configuration of the product formed depends on:

- the configuration of the reactant
- the number of conjugated double bonds or pairs of electrons in the reacting system
- whether the reaction is a thermal or a photochemical reaction

A photochemical reaction takes place when a reactant absorbs light

A thermal reaction takes place without the absorption of light

Electrocyclic reactions are concerted and stereospecific.

The thermal isomerization of *cis*-3,4-dimethylcyclobutene gives only *cis*,*trans*-2,4-hexadiene.

Heating its isomer, *trans*-3,4-dimethylcyclobutene, provides only *trans*,*trans*-2,4-hexadiene.



As the bond between carbons C3 and C4 in the cyclobutene is broken, carbon C2 and C5 must rehybridize from sp^3 to sp^2 and rotate to permit overlap between the emerging *p* orbitals and those originally present.

In such thermal cyclobutene ring openings, the carbon atoms are found to rotate *in the same direction,* either both clockwise or both counterclockwise. This mode of reaction is called a **conrotatory** process.

In the case of *cis*-3,4-dimethylcyclobutene, both the clockwise and counterclockwise courses result in the same product, *cis*,*trans*-2,4-hexadiene.

For *trans*-3,4-dimethylcyclobutene, two products are possible. The counterclockwise mode leads to *trans*,*trans*-2,4-hexadiene, while the clockwise direction would form *cis*,*cis* isomer (sterically encumbered).







The photochemical closure (photocyclization) of butadiene to cyclobutene proceeds with stereochemistry exactly opposite that observed in the thermal opening.

In this case, the products arise by rotation of the two reacting carbons in opposite directions. In other words, if one rotates clockwise, the other does so counterclockwise. This mode of movement is called **disrotatory**.



The six-membered ring of cyclohexadiene is formed **thermally** from *cis*-1,3,5-hexatriene by the **disrotatory** mode.

Heated *trans,cis,trans*-2,4,6-octatriene gives *cis*-5,6-dimethyl-1,3-cyclohexadiene, while *cis,cis,trans*-2,4,6-octatriene converts into *trans*-5,6-dimethyl-1,3-cyclohexadiene.



In contrast, the corresponding **photochemical** reactions occur in **conrotatory** fashion.





This stereocontrol is observed in many other electrocyclic transformations and is governed by the symmetry properties of the relevant π molecular orbitals.

The **Woodward-Hoffmann** rules describe these interactions and predict the stereochemical outcome of all electrocyclic reactions as a function of the number of electrons taking part in the process and whether the reaction is carried out photochemically or thermally.

TABLE 30-1 Stereochemical Rules for Electrocyclic Reactions			
Electron pairs (double bonds)	Thermal reaction	Photochemical reaction	
Even number	Conrotatory	Disrotatory	
Odd number	Disrotatory	Conrotatory	

Assign transition state as aromatic or antiaromatic based on number of electrons:

- Aromatic = Thermally allowed (Photochemically forbidden)
- Antiaromatic = Thermally forbidden (Photochemically allowed)

Determining the stereochemistry of the product of an electrocyclic reaction



(b)

(a)

(c)

Exercise 14-26

The cyclic polyene A (an "annulene") can be converted to either B or C by a sequence of electrocyclic ring closures, depending on whether light or heat are used. Identify the conditions necessary to effect either transformation and identify each step as either con- or disrotatory.



Solved Exercise 14-27

Heating *cis*-3,4-dimethylcyclobutene, A, in the presence of dienophile B gave exclusively the diastereomer C. Explain by a mechanism.



Exercise 14-28

Irradiation of ergosterol gives provitamin D_2 , a precursor of vitamin D_2 (a deficiency of which causes softening of the bones, especially in children). Is the ring opening conrotatory or disrotatory? (Caution: The product is written in a more stable conformation than that obtained upon ring opening.)



III. Sigmatropic Rearrangements

Migration of a σ -bond across a conjugated π -system

[m,n] shift when the σ -bond migrates across m atoms of one system and n of another



a [2,3] sigmatropic rearrangement



a [1,5] sigmatropic rearrangement



a [1,3] sigmatropic rearrangement



a [3,3] sigmatropic rearrangement



Consider the transition state of the reaction



Sigmatropic rearrangements have **cyclic** transition states.

Rearrangement must be **suprafacial** if the transition state has six or fewer atoms in the ring.



Woodward-Hoffmann Rules

TABLE 30-3 Stereochemical Rules for Sigmatropic Rearrangements			
Electron pairs (double bonds)	Thermal reaction	Photochemical reaction	
Even number	Antarafacial	Suprafacial	
Odd number	Suprafacial	Antarafacial	

THE CLAISEN REARRANGEMENT

At 200 °C, allyl phenyl ether undergoes an unusual reaction that leads to the rupture of the allylic ether bond. A σ bond migrates from one end of a conjugated π electron system to the other. The "conjugated π electron system" is the allyl group.



This transformation is a concerted reaction with an aromatic transition state (movement of six electrons). The initial intermediate is a high-energy isomer, which enolizes to the final product.



The Claisen rearrangement is general for other systems. With the nonaromatic allyl vinyl ether, it stops at the carbonyl stage because there is no driving force for enolization. This is called the **aliphatic Claisen rearrangement**.



The carbon analog of the Claisen rearrangement is called the **Cope rearrangement**; it takes place in compounds containing 1,5-diene units.



25

Exercise 22-24

Explain the following transformation by a mechanism. (**Hint:** The Cope rearrangement can be accelerated greatly if it leads to charge delocalization.)



migration of hydrogen



suprafacial rearrangement



antarafacial rearrangement

1,3-hydrogen shifts







Δ

 CD_2

1,5-hydrogen shifts



CD₂H

1,7-hydrogen shift



carbon migrating with one of its lobes interacting



carbon migrating with both of its lobes interacting



suprafacial rearrangement



antarafacial rearrangement



Suprafacial migration: Group moves across same face



Antarafacial migration: Group moves from one face to the other



Pericyclic Reactions in Biological Systems



References

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