

14. The Diels-Alder Cycloaddition Reaction

A. Introduction

In 1928, Otto Diels and his student Kurt Alder at the University of Kiel in Germany first reported their work in the reactions of electron poor alkenes with electron rich dienes to form substituted cyclohexenes. The importance of this reaction was realized over the course of the next 22 years and in 1950, Diels and Alder were awarded the Nobel Prize in chemistry.

The Diels-Alder reaction is also known as a [4 + 2] cycloaddition because it involves the concerted (no intermediate) reaction of a **four**-atom system with a **two**-atom system via a cyclic transition state. The four-atom system is a diene, while the two-atom system is a dienophile (alkene or alkyne). The product of the Diels-Alder reaction is a 6-membered ring containing a double bond (cyclohexene). The preparation of cyclic molecules is a difficult task in organic chemistry, which reveals why the Diels-Alder reaction is such a synthetically useful process.

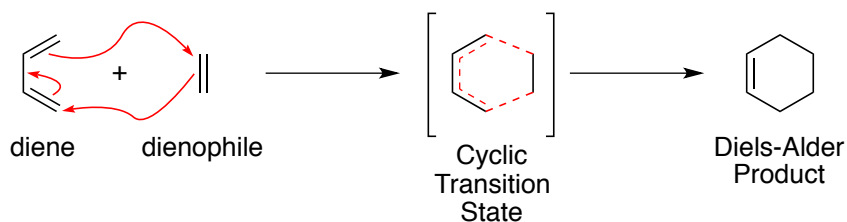


Figure 1. The Diels-Alder Reaction

The Diels-Alder reaction shown above between butadiene and ethene is the simplest example and is useful in showing how the atoms come together. In practice, however, this specific case does not work very well. Diels-Alder reactions work best when the dienophile contains one or more electron withdrawing groups as shown in figure 2.

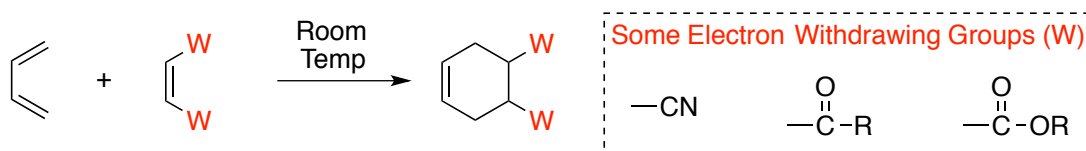


Figure 2. Diels-Alder Reaction with Electron Withdrawing Group on the Dienophile

The Diels-Alder reaction requires that the diene be oriented in the *s*-cis conformation for the reaction to take place. Acyclic dienes favor the lower energy *s*-trans conformation. A small equilibrium with the *s*-cis conformation does, however, exist, which is enough to allow the Diels-Alder reaction to take place. In the case of cyclic dienes, the diene is locked in the reactive *s*-cis conformation. For this reason, cyclic dienes are especially reactive in Diels-Alder reactions.



Figure 3. *s*-cis and *s*-trans Dienes

When a cyclic diene is used in a Diels-Alder reaction, a second ring is formed providing a bicyclic product. As shown in figure 4, cyclopentadiene will react with a dienophile to produce a new six-membered ring. The original five-membered ring of the diene is still present, however, and becomes part of a bridged bicyclic system. The product can be drawn as a flat representation or a more accurate three-dimensional representation.

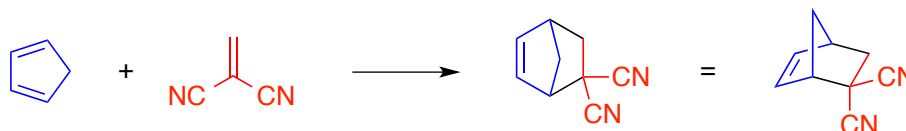


Figure 4. Diels-Alder Reaction to Produce a Bicyclic Product

In this laboratory experiment, you will be reacting cyclopentadiene and maleic anhydride in a Diels-Alder reaction. This reaction can produce two stereochemically different products: an *endo* product and an *exo* product. In most cases, such as in the reaction below, the *endo* product is formed more rapidly and is thus the favored product.

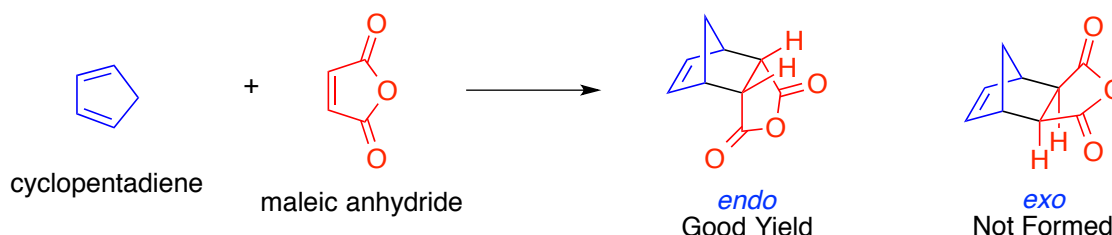


Figure 5. The Diels-Alder Reaction of Cyclopentadiene With Maleic Anhydride

The *endo* and *exo* products can be rationalized by looking at both *endo* and *exo* addition of the dienophile. With *endo* addition, the dienophile adds to the diene in such a way that the carbonyl substituents are “inside” or directly under the diene π-system during the addition. In the *exo* addition, the carbonyl substituents are “outside” and there is no overlap between these groups and the diene π-system during the addition process. The exact reasons for the *endo* preference are beyond the scope of the current discussion.

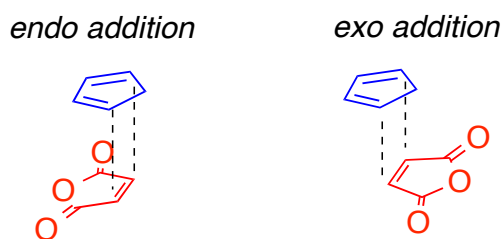


Figure 6. Endo vs Exo Addition

Cyclopentadiene, which will be used in this experiment cannot be purchased commercially, and must be prepared in the lab by thermally “cracking” dicyclopentadiene. The reason cyclopentadiene is not commercially available is due to that fact that on standing, two molecules of cyclopentadiene react with one another via a [4 + 2] cycloaddition to produce dicyclopentadiene (figure 7a). To obtain cyclopentadiene for use in your experiment, it will be necessary to thermally “crack” dicyclopentadiene as shown in figure 7b. This thermal cracking is

merely the reverse of the Diels-Alder reaction; thus it is called a Retro Diels-Alder reaction. The cracking process requires a very high temperature of 300 °C.

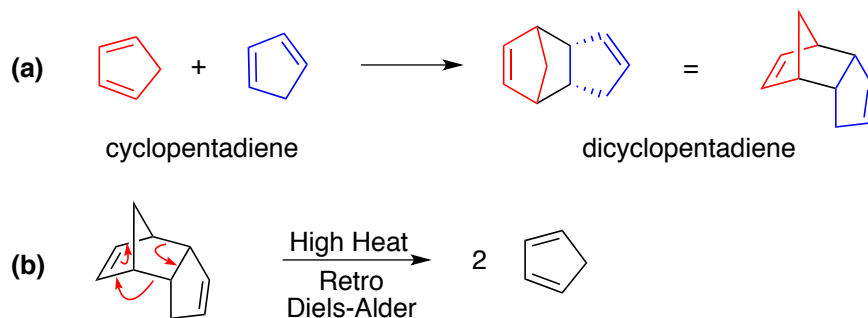


Figure 7: a. Cyclopentadiene Dimerization; b. Cracking Dicyclopentadiene

B. Experimental Procedure

Cracking Dicyclopentadiene to Obtain Cyclopentadiene

As discussed in the introduction, cyclopentadiene must be obtained by “cracking” dicyclopentadiene. The cracking procedure is carried out at 300 °C. Do not use a thermometer in the aluminum block as the thermometers in our lab do not go up to this temperature and will break under the high temperature conditions employed.

It is only necessary for two cracking apparatuses to be set up in each lab. This will provide enough cyclopentadiene for every student.

To a 5-mL conical reaction vial, add approximately 2 mL of paraffin oil and a spin vane then set up the cracking apparatus as shown in figure 8. Once assembled, support the entire assembly using a clamp. Before heating, check and confirm the following:

- All screw connections should be secure.
- The side-arm of the Claisen head should be sealed with a septum and a screw cap.
- The side-arm of the Hickman still should be closed off with a screw cap.

Turn the hot-plate to high and allow the apparatus to heat up for 10 min. At this point, the paraffin oil should be at approximately 300 °C, which is the temperature necessary to crack dicyclopentadiene. Fill the cold finger with ice water using a pipet. Be sure to periodically replace the ice water to ensure the cold finger stays cold during the entire cracking process. Fit a syringe with a needle and fill the syringe with dicyclopentadiene. Insert the needle through the septum on the Claisen head and slowly add dicyclopentadiene. The cracking process is rapid and you should be able to observe the cyclopentadiene (bp 42 °C) being collected in the Hickman still. Once a good amount of cyclopentadiene has been collected, the side-arm can be uncapped and the solution transferred to a small vial via pipet. At this point, you may begin using the cyclopentadiene for the second part of the experiment. Continue to add dicyclopentadiene via syringe until enough cyclopentadiene has been collected for everyone to perform the second part of the experiment. When finished, turn off the heat and allow the apparatus to cool before disassembly. *Return the cleaned Hickman still to your TA at the end of lab period. Do not lock it in your drawer!*

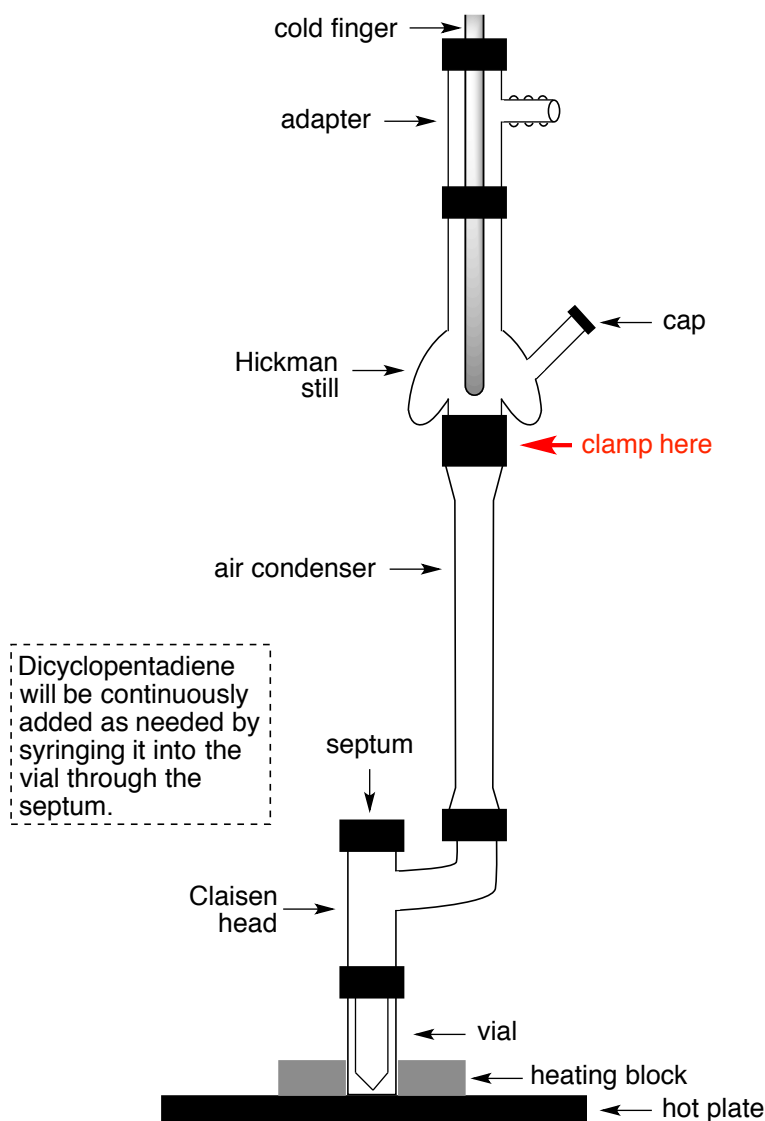


Figure 8. Cracking Apparatus

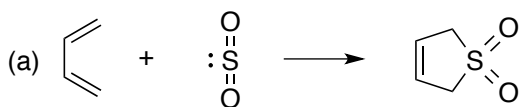
The Diels-Alder Reaction of Cyclopentadiene with Maleic Anhydride

The Diels-Alder reaction that you will be performing between cyclopentadiene and maleic anhydride occurs rapidly at room temperature. To aid in product isolation, the entire reaction will be carried out in the Craig tube.

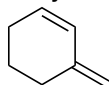
To the Craig tube, add 0.8 mL of reagent grade ethyl acetate and 175 mg of maleic anhydride. Stir the solution until the solid has dissolved. Add 0.8 mL of reagent grade hexane and mix well. Next, add 140 mg of cyclopentadiene. Wait for approximately 5 min then scratch the walls of the Craig tube to initiate crystallization. Cool the solution in an ice-bath and collect the crystals by centrifugation. Empty the crystals onto a pre-weighed watch glass. Determine the yield, melting point, and record an IR spectrum of the isolated product.

C. Pre-Lab Questions

1. If the Diels-Alder reaction is classified as a [4 + 2] cycloaddition reaction, how would you classify the cycloaddition reactions shown below?

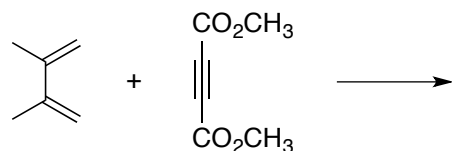
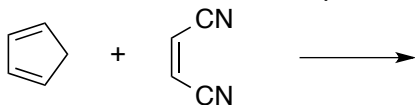


2. You are instructed to use 140 mg of cyclopentadiene ($d = 0.80 \text{ g/mL}$). It is typically more convenient to measure out a volume of liquid. What volume of cyclopentadiene should be used?
3. In the Diels-Alder reaction that you will be performing, which reagent will be limiting? Cyclopentadiene or maleic anhydride? Show your work!
4. Is it possible for the diene shown below to undergo a Diels-Alder reaction with maleic anhydride? Explain.



D. Post-Lab Questions

1. What do you suspect would have happened if 1.6 mL of ethyl acetate were used as the reaction solvent as opposed to a mixture of 0.8 mL of ethyl acetate and 0.8 mL of hexane? *Hint: refer to the crystallization experiment.*
2. Paraffin oil has a boiling point greater than $370 \text{ }^\circ\text{C}$. What was the purpose of adding paraffin to the reaction flask when cracking dicyclopentadiene?
3. Give the structure of the product for each Diels-Alder reaction shown below.



4. If you had conducted the reaction in a conical vial and then collected the crystals using a Hirsch Funnel, how do you think your percent yield would have changed? Explain.