

# Chapter 11

## Chemical Reactions

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*This chapter outlines and illustrates strategies for locating and verifying transition states for reactions as well as exploring changes in product distributions as a function of substituents and reactant stereochemistry.*

The treatment of chemical reactions adds an entirely new dimension to the application of quantum chemical models. While unique valence structures may generally be written for most molecules and, based on these structures, reasonable guesses at bond lengths and angles may be made, it is often difficult to designate appropriate valence structures for transition states, let alone specify detailed geometries. There is a complete absence of experimental data for the structures of transition states. However, transition-state geometries may be calculated. To aid in guessing starting geometries, **Spartan** provides both a small library of calculated transition-state structures for common reactions and a facility for automatically matching an entry in this library with the reaction at hand.\* The Spartan Reaction Database (SRD) as the library is called, also can be searched by substructure to yield all available transition states of reactions related to the one of interest.

**Spartan** also provides a procedure for driving user-defined coordinates. Aside from conformational analysis (see discussion in **Chapter 12**), the major application of this is to force reactions, thereby permitting identification of transition states.

The tutorials in this chapter illustrate **Spartan's** automatic procedure for guessing transition-state geometries based on SRD. They also illustrate the use of vibrational analysis (infrared spectroscopy) to verify that a particular structure indeed corresponds to a transition state and to show the motion leading it to reactants and products. The

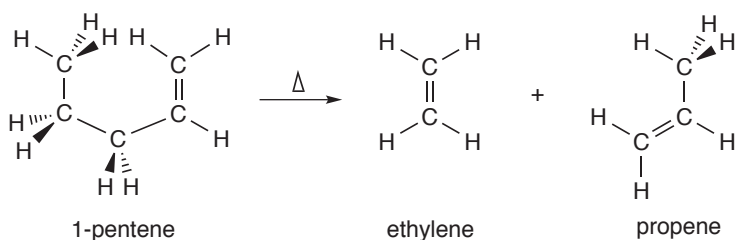
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\* Where a reaction is unknown to **Spartan's** library, a fallback technique which averages reactant and product geometries (similar to the so-called linear synchronous transit method) is invoked.




first four tutorials examine simple organic reactions, while the fifth tutorial provides an example of a transition state calculation for an organometallic reaction. The sixth tutorial illustrates how a reaction may be driven through a transition state. This tutorial, along with the fourth tutorial, draw the connection between relative activation energies and kinetic product distributions. The last tutorial in this chapter illustrates how transition states may be extracted from the Spartan Reaction Database.

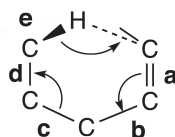
10 mins

## Ene Reaction of 1-Pentene







The proposed mechanism of the ene reaction involves simultaneous transfer of a hydrogen atom and CC bond cleavage. In this tutorial, you will obtain the transition state for the ene reaction of 1-pentene from an HF/3-21G calculation, and examine the reaction coordinate for evidence of concerted motion. While the HF/3-21G model is a less rigorous model than many available in *Spartan*, it is certainly good enough to illustrate the steps involved in obtaining and verifying a transition state.


1. Build 1-pentene in a conformation in which one of the terminal hydrogens on the ethyl group is poised to transfer to the terminal methylene group. To rotate about a (single) bond, first *click* on it to select (the bond will be encircled by a red arrow), and *drag* the mouse up or down in the area below  at the left of the screen. Alternatively, hold down the left button and **Alt** key (**option** key on Mac) and *drag* the mouse up and down. *Click* on .
2. Select **Transition State** from the **Search** menu (  ). *Click* on bond **a** in the figure on the following page and then *click* on bond **b**. A curved arrow from double bond **a** to single bond **b** will be drawn.

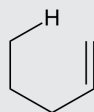



Next, *click* on bond **c** and then on bond **d**. A second curved arrow from bonds **c** to **d** will be drawn. Finally, *click* on bond **e** and then, *click* on the (methyl) hydrogen to be transferred and on the terminal (methylene) carbon to receive this hydrogen. A third curved arrow from bond **e** to the center of a dotted line that has been drawn between the hydrogen and oxygen will appear.

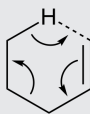
If you make a mistake, you can remove an arrow by selecting **Delete** from the **Build** menu () and then *clicking* on the arrow. Alternatively, hold down the **Delete** key as you *click* on an arrow. Select  to continue. With all three arrows in place, *click* on  at the bottom right of the screen. Your structure will be replaced by a guess at the ene transition state. If the resulting structure is unreasonable, then you have probably made an error in the placement of the arrows. In this case, select **Undo** from the **Edit** menu () to return to the model with the arrows and modify accordingly.

**Undo** is reserved for moving back from the transition-state structure (rather than from undoing reaction arrow placements).







You could also have used the 2D sketcher to provide the guess to the ene transition-state. Enter the sketcher  and draw 1-pentene. 2D sketches, do not include hydrogens and you need to draw a CH bond from the terminal  $\text{sp}^3$  carbon ( $\text{C}_5$ ).



*Click* on  in the icon bar above the sketch pane. *Click* on the CH bond and then on both H and the terminal  $\text{sp}^2$  carbon ( $\text{C}_1$ ). An arrow will be drawn. *Click* on the  $\text{C}_1\text{C}_2$  bond and then on the  $\text{C}_2\text{C}_3$  bond. A second arrow will be drawn. *Click* on the  $\text{C}_3\text{C}_4$  bond and then on the  $\text{C}_4\text{C}_5$  bond giving the third and final arrow.



Click on  to give the transition state guess and move to the main screen.

3. Select **Calculations...** from the **Setup** menu () and specify calculation of transition-state geometry using the HF/3-21G model. Select **Transition State Geometry** from the top menu immediately to the right of **Calculate**, and choose **Hartree-Fock** and **3-21G** from the two bottom menus. Finally, *check IR* to the right of **Compute**. This will allow you to confirm that you have found a structure that corresponds to a transition state, and that it smoothly connects reactant and product. Click on **Submit** and name it *ene reaction 1-pentene*.
4. When the job completes, animate the motion of atoms along the reaction coordinate. Select **Spectra** from the **Display** menu () and click on  in the bar at the top of the spectra pane and click on   in the palette that results. Click on  (Tables) at the left of the spectra pane to bring up a table of frequencies and intensities.

Calculated:







v	I
<input checked="" type="checkbox"/> 11689	0.01
<input type="checkbox"/> 503	0.01
<input type="checkbox"/> 552	0.25
<input type="checkbox"/> 633	0.10
<input type="checkbox"/> 819	0.16
<input type="checkbox"/> 876	1.00
<input type="checkbox"/> 979	0.03
<input type="checkbox"/> 1071	0.14
<input type="checkbox"/> 1092	0.91
<input type="checkbox"/> 1107	0.16
<input type="checkbox"/> 1133	0.55

Click the top entry in the list. It corresponds to an imaginary frequency, and will be designated with an **i** in front of the number.

Within the harmonic approximation, a vibrational frequency is proportional to the square root of the ratio of the force constant (reflecting the curvature of the potential surface along a particular coordinate) divided by a combination of the masses of atoms involved in motion along that coordinate. At a transition state (a

maximum in the reaction coordinate), the curvature is negative. Since the mass term is positive, the quantity inside the square root is negative and the frequency is an imaginary number.

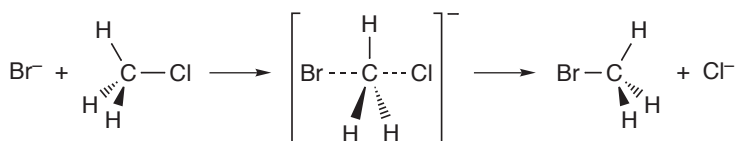
Is the vibrational motion consistent with an ene reaction of interest and not with some other process?







5. Click on  (Make List) at the left of the spectra pane. Controls in the dialog that result allow for changing both the amplitude of vibration (**Amp**) and the number of steps that make up the motion (**Steps**). The default number of steps (11) is fine but change the default amplitude. Click inside the box to the right of **Amp**: and enter **0.3** using the number pad that appears. Next, click on **Make List** at the bottom of the dialog. This will give rise to a group of 11 structures that follow the reaction coordinate down from the transition state (structure 6) both toward reactant and product. You are done with *ene reaction 1-pentene*, so close it.
6. Click on the list document, select **Calculations...** from the **Setup** menu () and specify calculation of **Energy** using the HF/3-21G model (the same level of calculation used to obtain the transition state and calculate the frequencies). Make certain that **Global Calculations** is checked and click on **OK**. Select **Surfaces** from the **Setup** menu () and specify evaluation of a bond density surface. Click on **More Surfaces...**, select **density (bond)** for **Surface** and **none** for **Property**. Before you click on **OK**, make certain that **Global Surfaces** is checked.
7. Submit the calculation\*. Name it *ene reaction 1-pentene sequence*. Once the job has completed, enter the **Surfaces** dialog, check the box to the left of density and examine the surface that you have calculated. Step through the sequence of structures ( and ) keys at the bottom of the screen) or animate the reaction (). Note, in particular, the changes in bonding revealed by the bond density surface.
8. Close *ene reaction 1-pentene sequence* and any open dialogs.

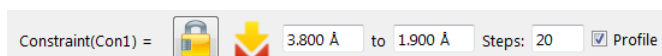
\* In this example, you have requested graphical surfaces prior to submitting the calculation. You could also have requested them to be done “on-the-fly” following the calculation.

## S<sub>N</sub>2 Reaction of Bromide and Methyl Chloride


The S<sub>N</sub>2 reaction passes through a transition state in which carbon is in a trigonal bipyramid geometry and the entering and leaving groups are colinear. In this tutorial, we will identify it as the “top” of a pathway leading smoothly from reactants to products, employing a semi-empirical molecular orbital model in order to minimize calculation time.
















1. Bring up the inorganic builder by selecting **New Build** from the **File** menu () and *clicking* on the **Inorganic** tab *click* on the atom bar, select C from the *Periodic Table* and the five-coordinate trigonal bipyramid () from the list of atomic hybrids and *click* on screen. Move to the organic builder (*click* on the **Organic** tab). Select Cl and *click* on one of the *axial* free valences. Select Br and *click* on the other *axial* free valence.
2. Select **Measure Distance** from the **Geometry** menu () and then *click* on the CBr bond. *Click* inside the box to the right of **Length** at the bottom right of the screen and enter **3.8** (3.8Å) using the number pad that appears. You have made a complex representing the reactant.
3. Select **Constrain Distance** from the **Geometry** menu (). *Click* on the CBr bond, and then *click* on  at the bottom right of the screen. The icon will change to  indicating a constraint is to be applied to this distance. *Check* the box to the left of **Profile** at the bottom of right of the screen. This will result in two additional text boxes.




Leave the value **3.8** (3.8Å) in the leftmost box alone, but change the number in the box to the right of **to**, to **1.9** (1.9Å). *Click* inside

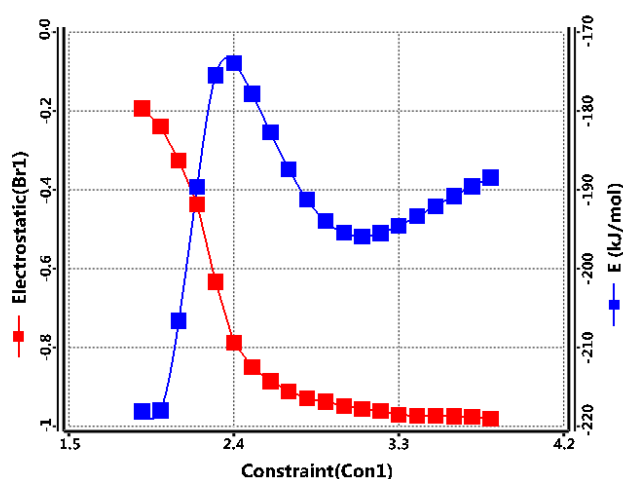
the box and use the number pad. In the same way, change the number in the box to the right of **Steps** from **10** (the default) to **20**. 20 Calculations with CBr bond lengths constrained from 3.8Å (the starting point) to 1.9Å (the ending point) will be performed. The transition state should have a CBr distance in between these values. Click on .

4. Select **Calculations...** from the **Setup** menu () and select **Energy Profile, Semi-Empirical** and **AM1** from the appropriate menus to the right of **Calculate** in the dialog that results. Make sure to change **Total Charge** to **Anion**.
5. Submit the job. Name it *bromide+methyl chloride*. When completed, it will give rise to a sequence of calculations placed in *bromide+methyl chloride.Prof.M0001*. You will be prompted as to whether you want to open this file. Click on **YES**. You can close the first document *bromide+methyl chloride*.
6. Align the molecules that make up the sequence. Click on  (**Geometry** menu), select **Structure** from the menu at the bottom right of the screen and, one after the other, click on the chlorine, the carbon and one of the hydrogens. Finally click the **Align by** button at the bottom right of the screen. Click on . Use the  and  keys at the bottom left of the screen to step through the reaction sequence.
7. Select **Spreadsheet** from the **Display** menu (). Click on **Add...** Select **E(kJ/mol)** from among the quantities listed in the **Molecule** tab. Next, enter the (constrained) CBr distances and bromine charges in the spreadsheet. Select **Constrain Distance** from the **Geometry** menu () click on the constraint marker in the model and click on  at the bottom right of the screen. Click on . Select **Properties** from the **Display** menu () to bring up a **Properties** dialog. Click on bromine and click on  to the left of **Electrostatic** under **Charges** in the **Atom Properties** dialog. Close the **Atom Properties** dialog. Close the spreadsheet.
8. Select **Plots** from the **Display** menu () to bring up the **Plots** dialog and click on  in the bar at the top of the dialog. Select



**Constraint (Con1)** (the distance at which the CBr bond has been constrained) from the **X Axis** menu, and both **E (kJ/mol)** and **Electrostatic (Br1)** from the **Y Axes** list in the dialog that results. Click on **Create**. By default, only the data points are displayed. Click on  in the bar at the top of the plots plane, select **Point-to-Point** and then click the down arrow to the right of the y-axis field and again, choose **Point-to-Point**, then click on **Done**.

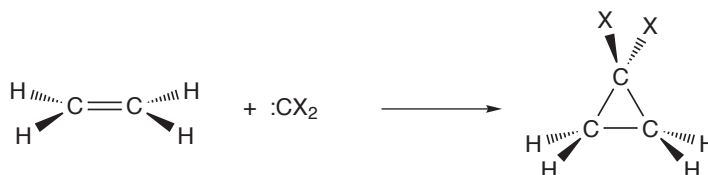
One plot gives the energy as the reaction proceeds and the other gives charge on bromine. Are the two related? Explain.



9. Close all documents and any open dialogs.

5 mins

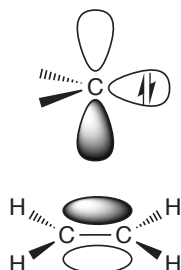
## Carbene Additions to Alkenes



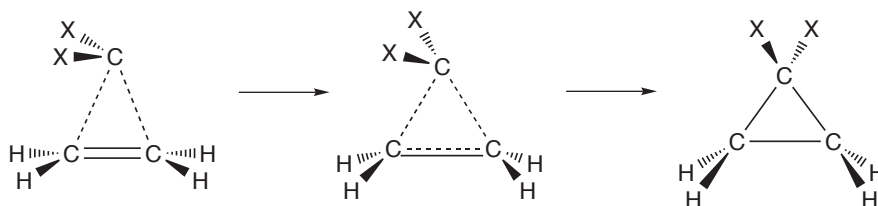
Singlet carbenes add to alkenes to yield cyclopropanes. A singlet carbene possesses both a high-energy occupied molecular orbital in the plane of the molecule, and a low-energy, out-of-plane unoccupied molecular orbital, and the reaction presents an interesting dilemma. It is clearly more advantageous for the low-lying vacant orbital on



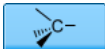



the carbene, and not the high-lying filled orbital, to interact with the olefin  $\pi$  system during its approach.



However, this leads to a product with an incorrect geometry, suggesting that the carbene needs to twist by  $90^\circ$  during the course of reaction.




In this tutorial, you will use the Hartree-Fock 3-21G model to obtain the transition state for addition of singlet difluorocarbene,  $\text{CF}_2$ , to ethylene and then analyze the motion of the fragments.

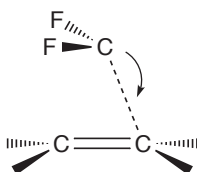
1. Build ethylene using the organic model kit.
2. Select  from the model kit. Hold down the **Insert** key (**option** key on Mac) and then *click* anywhere on screen. Alternatively, *double click* on a blank area of the screen. Next, select  from the model kit and *click* on two of the free valences on the  $\text{sp}^3$  carbon. Next, *click* on  and *click* on one of the remaining two free valences on the  $\text{sp}^3$  carbon. *Click* on  and *click* on the remaining free valence. You are left with two fragments, ethylene and difluorocarbene. Orient the two as to be poised for reaction.\*

\* Proper orientation of the two fragments is not crucial in this case, but is primarily to allow you to associate the arrows with the intended reaction. Proper orientation is, however, essential where different stereochemical outcomes are possible.

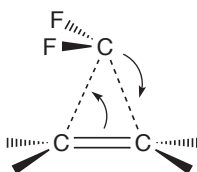



Translations and rotations normally refer to the complete set of fragments, but if you *click* on a fragment (not on a free valence) to select it, and then hold down the **Ctrl** key they will refer to an individual fragment.


3. Select **Guess Transition State** from the **Build** menu (). *Click* on the carbon on the CF<sub>2</sub> fragment and then *click* on the closer of the carbons on the ethylene fragment and finally *click* on the CF<sub>2</sub> carbon again. A dotted line is drawn between the two carbons that are to be bonded along with an arrow from the CF<sub>2</sub> carbon to the center of this line.









*Click* on the CC double bond and then *click* on the other ethylene carbon and on the CF<sub>2</sub> carbon. A second dotted line and arrow will be drawn.




*Click* on  at the bottom right of the screen. Your structure will be replaced by a guess at the transition state.

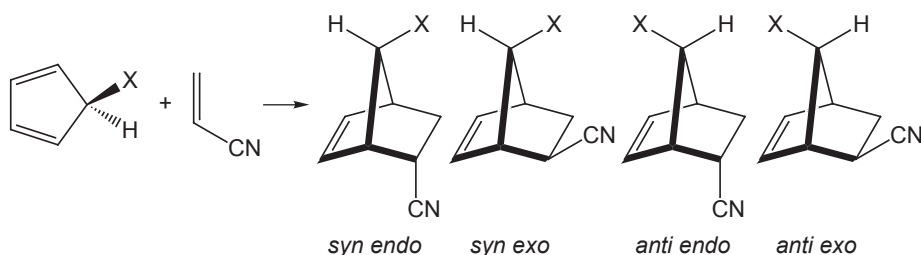
4. Select **Calculations...** from the **Setup** menu () and request calculation of a **Transition State Geometry** using the **HF/3-21G** model. *Check IR* to the right of **Compute**, and *click* on **Submit**. Name the job *difluorocarbene+ethylene*.
5. When the job is complete, examine the geometry of the transition state. In light of the previous discussion, would you describe your

structure as corresponding to an early or late transition state? Animate the vibration corresponding to the reaction coordinate. Select **Spectra** from the **Display** menu () *Click* on the  in the bar at the top of the spectra pane and select   from the resulting palette of choices. The “infrared spectrum” calculated for the transition state appears. *Click* on  at the far left of the spectra pane. This brings up a table of calculated frequencies and infrared intensities. The frequency at the top of the list should be preceded by an “i” designating it as imaginary. It corresponds to the reaction coordinate. Note the value of this frequency as well as that of the largest frequency.

*Click* in the check box corresponding to this frequency. Does the animation show that the carbene reorients as it approaches the double bond? Turn the animation off by again *clicking* in the imaginary frequency box. Close the **Spectra** pane and *click* on ()


6. Select **Properties** from the **Display** menu () and, in turn, *click* on each of the four hydrogens in the transition state. Change the value in the **Mass Number** menu in the **Atom Properties** dialog (**Properties** under the **Display** menu) from **1** to **2 Deuterium**. Resubmit the job. (No additional quantum chemical calculations are involved, but the vibrational analysis needs to be repeated.) When complete, examine the new set of vibrational frequencies, in particular, the imaginary frequency associated with the reaction coordinate. For comparison, examine the largest frequencies which corresponds to one combination of CH stretching motions. You will see that the value of the former has barely changed as hydrogen motions are not significantly involved in the addition reaction, whereas the latter has been markedly reduced.
7. Close *difluorocarbene+ethylene* and any open dialogs.

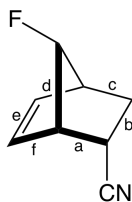
## Stereospecific Diels-Alder Reactions




Diels-Alder cycloaddition of 5-substituted cyclopentadienes with acrylonitrile can lead to four stereoproducts, in which the substituent, X, at the 5 position is *syn* or *anti* to the dienophile, and the nitrile is *endo* or *exo*. *Anti* products are preferred when X is alkyl while *syn* products are favored when X is halogen or alkoxy. In general, *endo* adducts are kinetically favored over *exo* adducts (see following tutorial).

In this tutorial, you will use HF/3-21G molecular orbital calculations to obtain both *syn* and *anti endo* and *exo* transition states for Diels-Alder cycloaddition of 5-fluorocyclopentadiene and acrylonitrile, and then use  $\omega$ B97X-D/6-31G\* calculations to estimate relative activation energies. We will use the stereoisomer generation tool introduced in *Spartan*'20 to simplify your work.

1. Build or sketch the substituted norbornene shown below (the product of *endo* addition of cyclopentadiene and acrylonitrile). Click on .

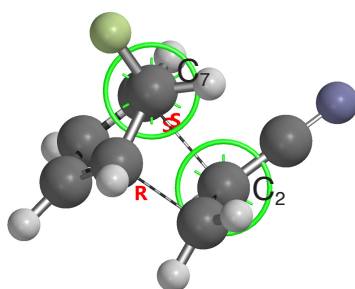


2. Select **Transition State** from the **Build** menu (). Click on bond **a** (see figure above) and then on bond **b**. A curved arrow will be drawn from **a** to **b**. Next, click on bond **c** and then on bond **d**; a second curved arrow from **c** to **d** be drawn. Finally, click on bond **e** and then on bond **f**, leading to a third curved arrow. The model on screen should now appear as follows.



Click on  at the bottom right to produce a guess at the transition state.

3. Select **Generate Isomers** from the **Geometry** menu and *click* on C<sub>2</sub> and C<sub>7</sub> in the transition state structure (which will be marked as chiral centers). They will be identified with green circles.



Click on **Generate List** to the right of **Isomers** at the bottom right of the screen, select **New Document** in the dialog that appears and *click* on **OK**. A list of the four stereoisomers will appear in a new document.

4. Select **Calculations** from the **Setup** menu. Specify **Energy** at **Ground** state in **Gas** from the three top menus to the right of **Calculate** and with **Density Functional**,  $\omega$ **B97X-D** and **6-31G\*** from the three bottom menus. Select **Transition State Geometry** using **Hartree-Fock** and **3-21G** from the three menus to the right of **Start From**. You have requested that transition state geometries for the four stereoisomers be calculated with the **HF/3-21G** model and following that energies calculated using the  $\omega$ **B97X-D/6-31G\*** density functional model. Make certain that **Global Calculations** at the bottom of the dialog is checked and *click* on **Submit**. Name the job **Diels-Alder stereochemistry**.
5. After the calculations have completed (a few minutes) select **Spreadsheet** from the **Display** menu. You can if you like replace the default labels (M0001, ...) by proper identifiers (*syn endo*,

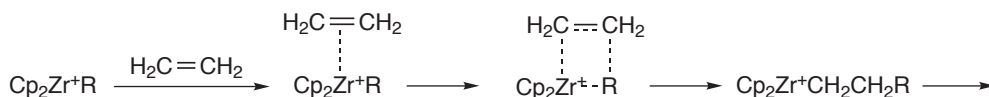
*syn exo*, *anti endo*, *anti exo*), to fit the stereoisomers. Click on **Add** at the bottom of the spreadsheet, and then on **Energy (au)** in the dialog that results. Identify the isomer with the lowest (most negative) energy and *click* on its label to select it. Again *click* on **Add** and then the **Molecule List** tab at the top of the dialog that results and finally *click* on **Relative Energy (kJ/mol)** in the dialog that results.

6. Close all documents and any open dialogs.



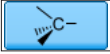
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## Ziegler-Natta Polymerization of Ethylene

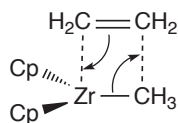
Ziegler-Natta polymerization involves a metallocene. This complexes an olefin, which then inserts into the metal-alkyl bond.












In this tutorial, you will use the semi-empirical PM3 model to obtain a transition state for insertion of ethylene into  $\text{Cp}_2\text{ZrCH}_3^+$  and, estimate the activation energy using the  $\omega\text{B97X-D/6-31G}^*$  density functional model.

1. Select **New Build** from the **File** menu () and then **Inorganic** from the menu at the top of the model kit. Click on the atom bar and select **Zr** from the *Periodic Table*. Select  from the list of hybrids and *double click* on screen. Select **Cyclopentadienyl** from the **Ligands** menu and *click* on two of the free valences on zirconium.
2. Select **Organic** from the menu at the top of the model kit to move to the organic model kit. Select  $\text{sp}^3$  carbon  and *click* on the remaining free valence on zirconium. Select **Alkenyl** from the **Groups** menu, hold down the **Insert** key (**option** key on Mac) and *click* anywhere on screen or *double click* in a blank area on screen.

- Orient the two fragments ( $\text{Cp}_2\text{ZrCH}_3$  and ethylene) as shown below:




(To move the fragments independently, hold down the **Ctrl** key and use the mouse while in the **Edit Build** mode.)

- Select **Guess Transition State** from the **Build** menu (). Click on the ZrC (methyl) bond and one after another, click on the methyl carbon and on one of the ethylene carbons. Next, click on the ethylene double bond and, one after another, click on the other ethylene carbon and on zirconium. Click on  at the bottom right of the screen. In a few seconds, a guess at the transition state appears.
- Select **Calculations...** from the **Setup** menu (). Specify a transition state geometry calculation using the PM3 semi-empirical model. Change **Total Charge** to **Cation** and check **IR** to the right of **Compute**. Click on **Submit** and name the job *Cp2ZrMe cation + ethylene*.
- When the job has completed, select **Spectra** from the **Display** menu (). Click on the  in the bar at the top of the spectra pane and select . The “infrared spectrum” calculated for the transition state appears. Click on  at the far left of the spectra pane. This brings up a list of calculated frequencies and infrared intensities. The frequency value at the top of the list should be preceded by an “i”, designating it as imaginary. Click on this frequency and examine the vibrational motion.
- Perform density functional energy calculations using PM3 geometries to obtain a better estimate for the energy barrier for ethylene insertion. Select **Save As** from the **File** menu () to make a copy of *Cp2ZrMe cation+ethylene*; name it *Cp2ZrMe cation+ethylene density functional*. Select **Calculations...** from the **Setup** menu () and specify calculation of energy using the  $\omega$ B97X-D/6-31G\* density functional model. *Spartan* will



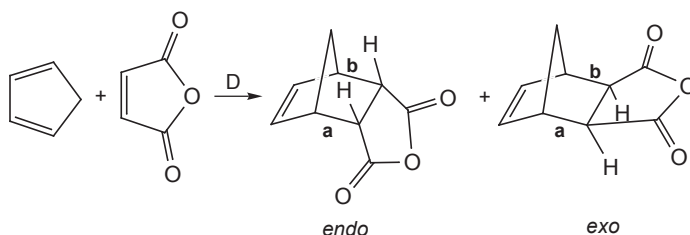
automatically make use of a pseudopotential for Zr instead of the all-electron 6-31G\* basis set. Remove the checkmark on **IR** (to the right of **Compute**). **Total Charge** should still be set to **Cation**. Click on **Submit**.

8. While you are waiting for the energy calculation to complete, build both ethylene and  $\text{Cp}_2\text{ZrCH}_3^+$  (name them *ethylene density functional* and *Cp2ZrMe cation*, respectively). For  $\text{Cp}_2\text{ZrCH}_3^+$ , start with three-coordinate trigonal Zr, and then add two cyclopentadienyl ligands and a four-coordinate tetrahedral carbon. For each, select **Calculations...** from the **Setup** menu () and specify calculation of energy using the  $\omega\text{B97X-D/6-31G}^*$  density functional model. Select **Equilibrium Geometry**, **Semi-Empirical** and **PM3** from the three menus to the right of **Start From** to designate use of a PM3 geometry. For *Cp2ZrMe cation density functional* (only), set **Total Charge** to **Cation**. Make certain that **Global Calculations** at the bottom of the **Calculations** dialog is **not** checked.
9. Submit both jobs. When they have completed, calculate an activation energy for the insertion reaction (subtract the sum of the energies of ethylene and  $\text{Cp}_2\text{ZrMe}$  cation from the energy of the calculated transition state).
10. Close all documents and any open dialogs.







15 mins

## Thermodynamic vs. Kinetic Control










Chemical reactions may yield different products depending on the conditions under which they are carried out. High temperatures and long reaction times favor the most stable (thermodynamic) products, whereas low temperatures and short reaction times favor the most readily formed (kinetic) products. For example, the kinetic product in Diels-Alder cycloaddition of cyclopentadiene and maleic anhydride is the *endo* adduct, whereas it seems likely that the less-crowded *exo* adduct is the thermodynamic product.

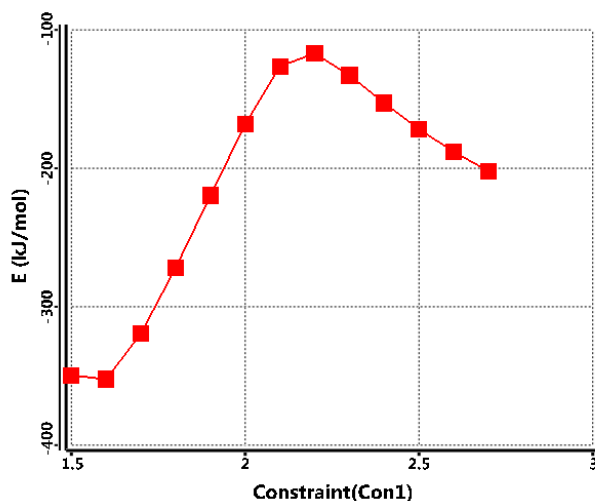


Here you will first obtain pathways for reactions leading to both *endo* and *exo* adducts using the PM3 semi-empirical model and then follow these by  $\omega$ B97X-D/6-31G\* energy calculations to get a better estimate of the difference in activation energies.

1. Build or sketch the *endo* Diels-Alder adduct of cyclopentadiene and maleic anhydride.
2. Select **Constrain Distance** from the **Geometry** menu () and *click* on bond **a** in the figure above. *Click* on the icon  at the bottom right of the screen (it will then turn to ). *Check* the box to the left of **Profile** in the middle of the screen. This will give rise to three additional check boxes. Change the value in the leftmost box to 1.5Å by *clicking* inside the box and entering **1.5** using the number pad. In the same way, enter **2.7** (2.7Å) and **13** (13 steps) into the boxes to the right of **to** and **Steps**, respectively. You have specified that bond **a** will be constrained first to 1.5Å, then to 1.6Å, then to 1.7Å, etc. and finally to 2.7Å. *Click* on . Make certain that **Global Steps** to the right of **Profile** is *checked*. This means that the two bonds will move in concert.
3. Repeat the process for bond **b**. When you are done, both bonds **a** and **b** will be constrained from 1.5Å to 2.7Å in 13 equal steps. *Click* on .
4. Select **Calculations...** from the **Setup** menu () and select **Energy Profile** from the top menu to the right of **Calculate**, and **Semi-Empirical** and **PM3** from the two bottom menus in the dialog that results. *Click* on **Submit** at the bottom of the dialog. Name it *cyclopentadiene+ maleic anhydride endo*.
5. When completed, the job will give rise to a new document *cyclopentadiene+maleic anhydride endo.Prof.M0001*. This

contains 13 calculations corresponding to the 13 steps that make up the energy profile. You will be prompted as to whether you want to open this file. *Click* on **Yes**.\*

6. Select **Spreadsheet** from the **Display** menu () and *click* on **Add...** at the bottom of the spreadsheet. Select **rel. E (kJ/mol)** from among the entries in the **Molecule List** tab and *click* on the spreadsheet to release the **Add** menu. Next, *click* on **Constrain Distance** from the **Geometry** menu () and *click* on one of the two CC bonds varied in the energy profile. *Click* on  at the bottom right of the screen. Close the spreadsheet by again selecting it or *clicking* on  or by *clicking* on  at the top right. *Click* on . Select **Plots** from the **Display** menu () and *click* on  to bring up the **Add Plots** dialog. Select **Constraint (BondX)\*\*** from among the items in the **X Axis** menu and **E (kJ/mol)** from the **Y Axes** list and *click* on **Create**. By default, only the data points are displayed. *Click* on  in the bar at the top of the plots plane, select **Point-to-Point** in the resulting **Edit Plot** dialog and then *click* on **Done**.






Identify both the reactant and transition state from the plot and estimate the activation energy for the cycloaddition reaction.

7. Repeat steps 1 to 6 for the *exo* adduct. Compare the activation

\* To avoid confusion, it is a good idea to close the original file *cyclopentadiene+maleic anhydride endo*.

\*\* Bonds are numbered in the order they were formed upon initial construction of the molecule.

energy for *exo* addition to that for *endo* addition (above). What is the kinetic product?

- Open *cyclopentadiene+maleic anhydride endo.Prof.M0001* () and make a copy (). Name it *cyclopentadiene +maleic anhydride endo DFT*. Select **Calculations** from the **Setup** menu () and specify an energy calculation with the  $\omega$ B97X-D/6-31G\* model in the dialog that results. Make sure that **Global Calculations** at the bottom of the dialog is checked. Click on **Submit**. When completed, perform the same spreadsheet and plot operations you did for the PM3 calculations.
- Repeat the above procedure for the *exo* adduct and compare the two activation energies. What is the kinetic product?
- Close all documents and any open dialogs.




1 min

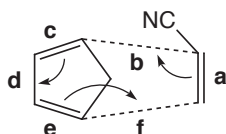
## Activation Energies of Diels Alder Reactions


In an earlier tutorial, *Dienophiles in Diels-Alder Reactions* (Chapter 8), you looked for a correlation between LUMO energies for a series of related dienophiles and relative rates of Diels-Alder cycloadditions involving cyclopentadiene. In this tutorial, you will compare calculated activation energies for this same set of reactions with the experimental rates. You will use the previous set dienophiles and obtain transition states from the Spartan Reaction Database (SRD). The only quantum chemical calculation that is required is for cyclopentadiene.

- Build or sketch cyclopentadiene. Select **Append Molecule(s)...** from the **File** menu, locate the file *Diels-Alder dienophiles* (from Chapter 8) and click on **Open**. If you have not yet completed this tutorial, you can find this file in the *organic reactions* folder inside the *Tutorials\** directory.

\* For Windows, this directory is found in *Program Files/Wavefunction/Spartan20*. For security reasons, the program file directory is protected. Copy the folder to your desktop or to another location available to the user prior to opening it in *Spartan*. For Linux, this is found in the directory where *Spartan* was installed. For Macintosh, this is located at the top level on the *Spartan20* disc image.



2. Open the **Spreadsheet** from the **Display** menu (). Click on the **Label** header cell and then *right click* and choose **Rename Selected Using SSPD** from the contextual menu that results. Close the **Spreadsheet** when finished.
3. Select **Calculations...** from the **Setup** menu (). Specify an **Equilibrium Geometry** calculation using the **Hartree-Fock 3-21G** model. Make sure the **Global Calculations** box is checked. Submit the job with the name *Diels-Alder reactants*.\*
4. Select **New Build** from the **File** menu (). **Build** cyclopentadiene, select **Alkenyl** from the **Groups** menu, hold down the **Insert** key (**option** key on Mac) and *click* on screen (or *double click* in a blank area on screen). Cyclopentadiene and ethylene will both appear on screen, although they will not be connected. Select **Cyano** from the **Groups** menu and *click* on one of the free valences on ethylene. Both cyclopentadiene and acrylonitrile will appear on screen.
5. Orient the two molecules such that they are poised for a Diels-Alder reaction leading to an *endo* product.

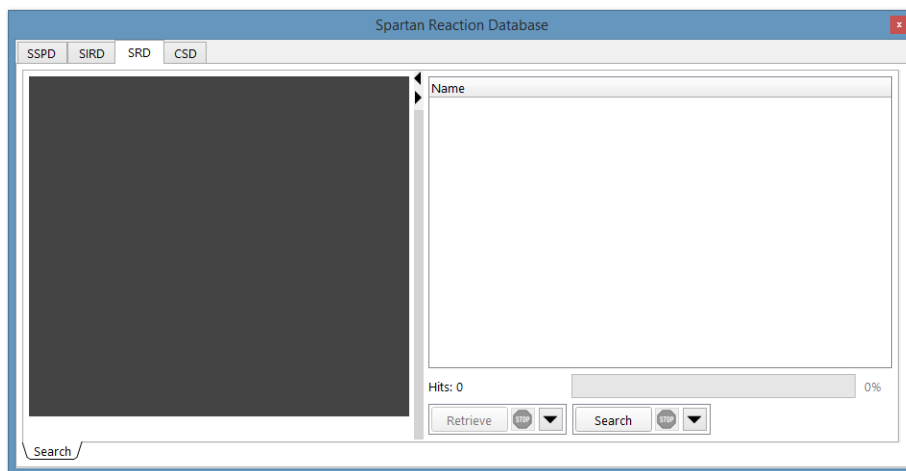



Select **Reaction Query** from the **Search** menu ().\*\* Click on the bond marked **a** in the above figure and then *click* on the two carbons that when connected will lead to the bond marked **b**. A dotted line will be drawn between these carbons and a curly arrow drawn from the center of bond **a** to the center of bond **b**. Next, *click* on bond **c** and then on bond **d**. A second arrow will be drawn. Finally, *click* on bond **e** and, *click* on the two carbons that when connected will lead to the bond marked **f**. A second dotted line and a third arrow will be drawn.

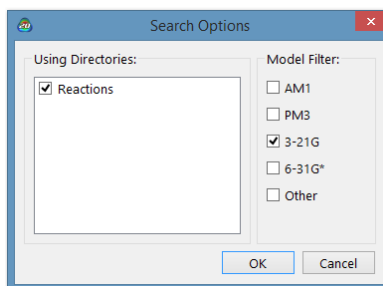
\* *Spartan* identifies calculations that have already been done, in this case, the set of dienophiles. The only calculation remaining is that for cyclopentadiene.

\*\* **Reaction Query** is equivalent to **Transition State** for the purpose of defining curly arrows. It lacks the ability to automatically guess a transition state.

6. Select **Structure Query** from the **Search** menu (  ). *Click* on all three free valences on the acrylonitrile fragment. They will be replaced by orange cones, meaning that anything (including hydrogen) may be attached to these positions.
7. Select **Databases** from the **Search** menu (  ) and *click* on the **SRD** tab at the top of the dialog that results. This leads to the **Spartan Reaction Database (SRD)** dialog.

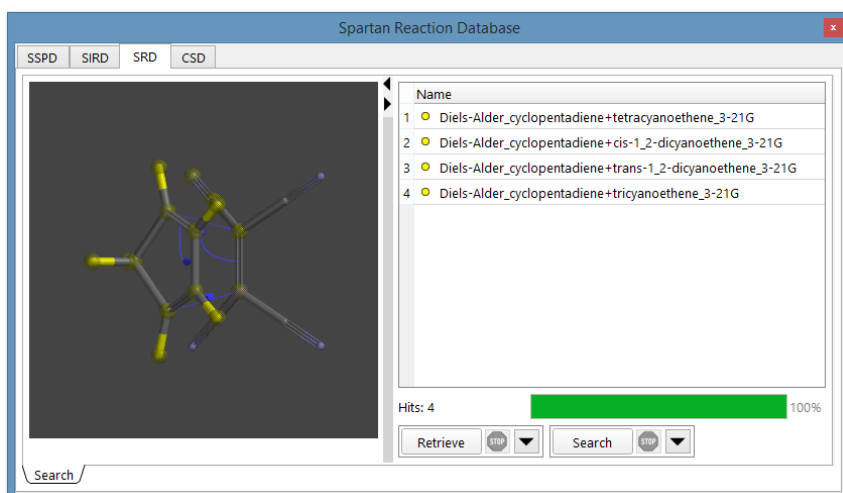



Before you begin the search, *click* on  to the right the **Search** button at the bottom of the dialog. This brings up the **Search Options** dialog.




*Check 3-21G* under **Method Filters** and *click* on **OK**. *Click* on the **Search** button to search the Spartan Reaction Database for Diels-Alder transition states between cyclopentadiene and substituted acrylonitriles.

8. When the search completes, a listing of hits appears at the right of the dialog.



This should contain four Diels-Alder transition states for *endo* additions of cyclopentadiene and *trans*-1,2-dicyanoethylene, *cis*-1,2-dicyanoethylene, tricyanoethylene and tetracyanoethylene. All need to be retrieved into a single document. Click on  to the right of the **Retrieve** button at the bottom of the dialog to bring up the **Retrieve Options** dialog. Make sure that **New Document** is selected in this dialog and click on **OK**. Hold down the **Ctrl** key, select (click on) all four Diels-Alder transition states and click on **Retrieve** at the bottom of the dialog. A new (unnamed) document will be created. Close the file and save it as ***Diels-Alder transition states***.

9. As soon as ***Diels-Alder reactants*** completes, select **Append Molecule(s)...** from the **File** menu, navigate to ***Diels-Alder transition states*** and click on **Open**.
10. Select **Reactions** from the **Display** menu (). One after the other, calculate activation energies for the six Diels-Alder reactions. Use cyclopentadiene and one of the dienophiles for **Reactants** and the appropriate transition state and **none** for **Products**. Select **Current Document** under **Source** at the bottom of the dialog,  $\Delta E$  under **Calculate** and click on **Compute**. Is the ordering calculated activation energies consistent with the experimental relative rates (available in the tutorial ***Diels-Alder dienophiles*** in **Chapter 8**)?
11. Close all documents and any open dialogs.