

CD-ROM Appendix J: Use of Computational Chemistry Software Packages

Thermodynamic properties of molecular species that are used in reactor design problems can be readily estimated from thermodynamic data tabulated in standard reference sources such as *Perry's Handbook* or the JANAF Tables. Thermochemical properties of molecular species not tabulated can usually be estimated using group contribution methods. Estimation of activation energies is, however, much more difficult due to the lack of reliable information on transition state structures, and the data required to carry out these calculations is not readily available. Recent advances in computational chemistry and the advent of powerful easy-to-use software tools have made it possible to estimate important reaction rate quantities (such as activation energy) with sufficient accuracy to permit incorporation of these new methods into the reactor design process. Computational chemistry programs are based on theories and equations from quantum mechanics, which until recently could only be solved for the simplest systems such as the hydrogen atom. With the advent of inexpensive high-speed desktop computers, the use of these programs in both engineering research and industrial practice is increasing rapidly. Molecular properties such as bond length, bond angle, net dipole moment, and electrostatic charge distribution can be calculated. Additionally, reaction energetics can be accurately determined by using quantum chemistry to estimate heats of formation of reactants, products, and also for transition state structures.

Examples of commercially available computational chemistry programs include Spartan, developed by Wavefunction, Inc. (<http://www.wavefun.com>) and Cerius³, from Molecular Simulations, Inc. (<http://www.msi.com>). The following example utilizes Spartan 4.0 to estimate the activation energy for a nucleophilic substitution reaction (S_N2).

CDJ.1 Example: Estimation of Activation Energies

Synthesis of chemical-grade ethanol can be carried out by a nucleophilic substitution reaction using hydroxide ion as the nucleophile and a haloethane as the substrate. For this problem, we will investigate the activation energy for the reaction:



This noncatalytic reaction takes place in water at moderate temperatures. In order to investigate the energetics of this reaction, Spartan 4.0 will be used to estimate the data required to carry out the following calculations:

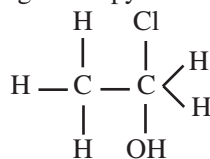
- a) The heat of formation of all reactants and products (including the ionic species) and the overall enthalpy change for the reaction:

$$\Delta H_{\text{Rx}} = \sum H_f^\circ(\text{Products}) - \sum H_f^\circ(\text{Reactants})$$

- b) The activation energies for the forward and reverse reactions based on an assumed model for the transition state species.

From organic chemistry, we learn that the mechanism for $\text{S}_{\text{N}}2$ (substitution, nucleophilic, bi-molecular) reactions involves backside attack of the nucleophile at the carbon atom where a suitable leaving group (such as a halogen atom) is attached. The entering and leaving groups are presumed to be simultaneously bonded in axial positions at the carbon atom where the reaction takes place, hence requiring a particular geometry for the transition state that accommodates this arrangement. The following approximations can be used to obtain a reasonable structure for the transition state species for this and other $\text{S}_{\text{N}}2$ reactions:

- Assume that the geometry of the carbon atom where the nucleophilic attack takes place is trigonal-bipyramidal;



- Arrange the entering and leaving groups in axial positions at this carbon atom (e.g., 180° apart)
- Bond distances for the entering and leaving groups will be constrained to be somewhat larger than is typical for normal covalent bonds signifying the simultaneous formation and cleavage of bonds for the attacking hydroxide ion and the leaving group

We first set up the calculation for the transition state species using the following step-by-step procedure.

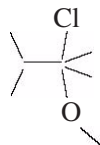
1. Start Spartan, click on *File/New* to enter the Builder. Due to the non-standard geometry at the reaction center, the Expert Builder must be used (click on Expert tab on the right).
2. Click on carbon (C) in the periodic table and choose the normal tetrahedral geometry for the carbon atom not involved in the reaction $\text{---x} \leftarrow$. To place the atom in the workspace, move the mouse pointer to the builder page and click once (left mouse button).
3. With carbon still selected as the atom, select trigonal-bipyramidal

geometry from the bonding geometry menu $\text{---x} \leftarrow$ and click on any

free valance of the first carbon (shown in yellow).

4. To complete the transition state structure, click on chlorine as the atom and select terminal geometry (---x) and click on an axial free valance for the carbon atom where the reaction is to take place. Now select oxygen with angular geometry, $\text{---x} \searrow$, and click on the other-axial free valance shown on the screen. Hydrogen atoms can now be added at all other free valences, but Spartan assumes that any unsatisfied free valance is saturated and automatically assigns a hydrogen atom to each of the yellow bonds.

The following schematic should be shown on the screen:



5. Click on *Minimize* in the *Build* menu. This performs a crude energy minimization calculation.
6. We now wish to constrain (i.e., set) the bonds at the reaction center to values that are somewhat larger than would be characteristic of C—O and C—Cl covalent bonds in normal molecules. In the builder, perform the following steps:
 - Click on *Geometry/Constrain Distance* and click on one of the two bonds involved in the reaction
 - In the lower right-hand corner, there will be a button with a pink lock on it. Click on this button to unlock the bond length for the selected bond. Next to that button, the current bond distance will appear (about 1.77 for C—Cl and 1.42 for C—O). Delete that value and enter a value that is about 50% bigger (2.5 works well).
7. Click on *Minimize* from the *Build* menu to perform a crude energy minimization of the constrained transition state structure and save the result (*File/Save—Yes*/supply a name). The appearance of the molecule can be changed by selecting different renderings (*ball and wire*, *ball and spoke*, *tube*, etc.) in the *Model* pull-down menu: experiment with some models to find one that you like best. The molecule can be

rotated and translated using the left and right mouse buttons, respectively.

8. We are now ready to carry out some quantum chemistry calculations in order to first examine the feasibility of our assumed transition state structure, and then calculate the energy (heat of formation) of the transition state. To determine if we have a good approximation for the transition state for this reaction, carry out the following calculations:
 - Select *Setup/Calculations*
 - In the window that appears, there are six different sections to modify the calculations Spartan will perform. In the *Calculate* section there are four pull-down menus. In the top left menu, select *Single Point Energy*. The other three menus should be correct without changing anything (they should read *Ground*, *Semi-Emperical*, and *AMI*).
 - Total Charge to Anion. {Note: the charge on the transition state is equal to the summation of the formal charges of all atoms in the molecule. The formal charge on the carbon atom where the reaction is occurring is $\text{Formal Charge} = \# \text{ valence electrons} - \# \text{ non-bonding electrons} - 1/2 (\# \text{ bonding electrons}) = 4 - 0 - 1/2 (10) = -1$ }
 - Multiplicity = 1 {Note: the spin multiplicity is the number of unpaired electrons plus 1. The transition state has no unpaired electrons.}
 - The *Constraints* button in the Subject to dialog window should be clicked off for this calculation.
 - Check the *Freq.* box from the *Compute* section. Then select *Submit* in the lower right-hand corner of the screen. Depending on the speed of your computer, the requested calculation may take several minutes (5 or more).
 - When the calculation is complete, click OK to remove the dialog box and select *Display/Vibration*. From quantum mechanics we know that the normal mode vibration of a transition state species will be an imaginary frequency. Examine the list of vibrational frequencies: there should be at least one imaginary frequency, and several (three in this case) may be listed. To determine which imaginary frequency corresponds to the reaction that we are studying, we will use the animation utility in Spartan to visualize the vibrational motion.
 - Click on the imaginary frequency around 458.
 - Change the default value from 7 frames to 25 *steps* to slow down the animation. Does this correspond to the reaction? No, this frequency corresponds to a “wag” of the methyl group.
 - Examine the other imaginary frequencies until you identify the one that corresponds to the reaction of interest—normally this will be the imaginary frequency with the largest value (around 540 in this case). For our assumed transition state, the imaginary frequency at

about 112 has the correct bonds involved, but the action shown indicates an elimination reaction rather than substitution. Animate the 540 normal mode and convince yourself that this frequency corresponds to the correct reaction coordinate.

9. We will now use Spartan to calculate the heat of formation of the transition state.
 - *Select Setup*
 - From the *Calculate* section, change the top left pull-down menu to *Transition State Geometry*.
 - *Select Submit* to start the calculation. Click on OK to clear the dialog box. Spartan is now using quantum mechanics to search the potential energy surface looking for a global saddle point that defines the transition state (including solvation effects). This calculation will take several minutes. Click on OK when the dialog box appears indicating that the job has finished.
10. Retrieve the calculated heat of formation. Select *Display/Properties/Energy*. A value close to -121.835 kcal/mol should be obtained. Select *Display/Vibration*; only one imaginary frequency should appear. Animate the frequency to be sure that it is the correct one.
11. Build (*File/New*) and *Minimize* both ethyl chloride and ethanol using either the entry or expert builders. Save the structures, and in the main window determine the heat of formation for each molecule using the following steps:
 - *Setup/Semi-empirical*
 - Task Geometry Optimization, (a change from the previous setup)
 - Model AM1
 - Charge 0 (a change from previous setup)
 - Multiplicity 1

Click on OK to clear the dialog box. This calculation will be quicker than the transition state search. Click on OK when the dialog box appears indicating that the calculation has finished, and retrieve the estimated heat of formation (*Display/Properties/Energy*). Values very close to the following should be obtained:

$$H_f^\circ \text{ for ethanol} = -69.164 \text{ kcal/mol}$$

$$H_f^\circ \text{ for ethyl chloride} = -26.649 \text{ kcal/mol}$$

Note: Because of the solution technique and local minima, slightly different values may result.

12. Build the Cl^- ionic species in the expert builder by selecting chlorine with terminal geometry ($-\text{x}$) and then deleting the free valence. Select *Delete Atom*, click on the very top of the bond from the Cl atom, and then enter a period (i.e., "." from the keyboard). Do not minimize the chlorine *atom* (there is nothing to minimize!), save, and exit to the main Spartan window.

13. Build the OH⁻ ion by selecting oxygen in the expert builder with terminal geometry (—x). Again, do not minimize: save, and exit to the main Spartan window.
14. Calculate the heats of formation for each of the two ionic species. The following commands should be used to set up and execute the calculations:
 - *Setup*
 - Task = Single Point Energy (a change from previous setup)
 - Model AM1
 - Charge = -1 (a change from previous setup)
 - Multiplicity 1
 - Save
15. Click on OK to clear the dialog box indicating that the job has been submitted. These calculations will take only a few seconds as the geometry of the ion is not being changed to find a global energy minimum. Values close to the following should result:

$$H_f^\circ \text{ for OH}^- = -122.206 \text{ kcal/mol}$$

$$H_f^\circ \text{ for Cl}^- = -114.669 \text{ kcal/mol}$$

16. Use the heats of formation to calculate the heats of reaction and activation energy.

$$\begin{aligned} \Sigma H_f^\circ(\text{Reactants}) &= H_f^\circ(\text{C}_2\text{H}_5\text{Cl}) - H_f^\circ(\text{OH}^-) \\ &= -26.65 + -122.2 \\ &= -148.85 \text{ kcal/mol} \end{aligned}$$

$$\begin{aligned} \Sigma H_f^\circ(\text{Products}) &= H_f^\circ(\text{C}_2\text{H}_5\text{OH}) + H_f^\circ(\text{Cl}^-) \\ &= -69.16 + -144.67 \\ &= -183.83 \text{ kcal/mol} \end{aligned}$$

For the forward reaction

$$\begin{aligned} E_A &= H_f^\circ(\text{Transition state}) - \Sigma H_f^\circ(\text{Reactants}) \\ &= -121.85 - (-148.85) = 27 \text{ kcal/mol} \end{aligned}$$

For the reverse reaction

$$\begin{aligned} E_{Ar} &= H_f^\circ(\text{Transition state}) - \Sigma H_f^\circ(\text{Products}) \\ &= -121.85 - (-183.83) \\ &= 62 \text{ kcal/mol} \end{aligned}$$

$$\begin{aligned}\Delta H_{\text{Rx}}^{\circ} &= \sum H_f^{\circ}(\text{Products}) - \sum H_f^{\circ}(\text{Reactants}) \\ &= -183.83 - (-148.85) \\ &= -35 \text{ kcal/mol}\end{aligned}$$

17. The complete reaction energy diagram is shown below.

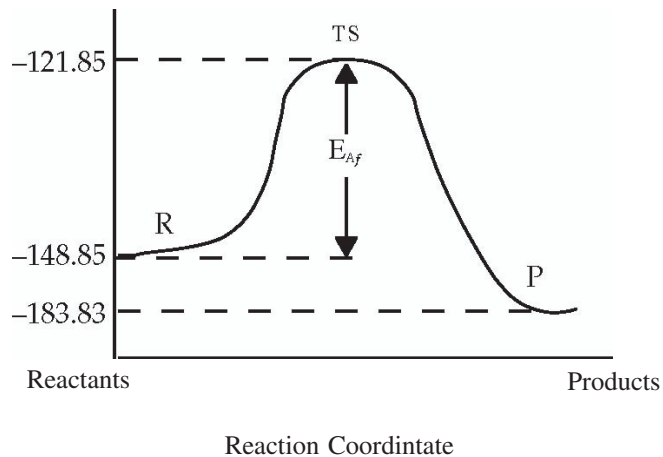


Figure CDJ-1 (Example provided by Professor Robert M. Baldwin, Chemical Engineering Department, Colorado School of Mines in Golden, Colorado.)

CDPApp.J-1A Redo Example Appendix J.1.

- Choose different methods of calculation such as using a value of 2.0 Å to constrain the C—Cl and C—O bonds.
- Choose different methods to calculate the potential energy surface. Compare the ab initio to the semi-empirical method.
- Within the semi-empirical method, compare the AM1 and PM3 models.