

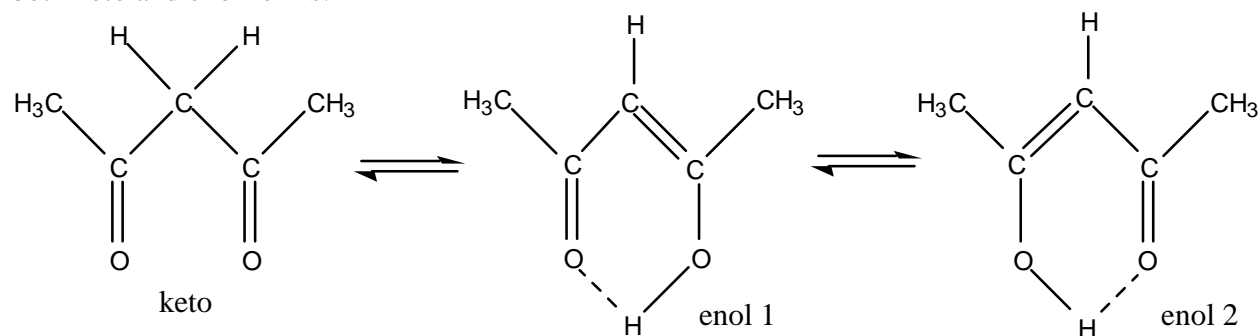
Determination Of Enthalpy Of Enolization By NMR

Purpose

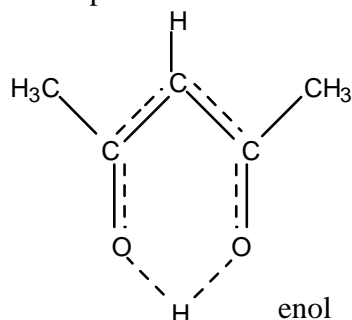
The equilibrium constant, enthalpy, entropy, and Gibbs energy for the keto-enol tautomerization of acetylacetone will be determined using NMR. (Note the pre-lab assignment, below).

Theory

2,4-Pentanedione (acetylacetone) and other β -diketones undergo a tautomeric shift and exist in both keto and enol forms:



Enol 1 and enol 2 are indistinguishable. For the sake of predicting the enol spectrum, it is convenient to use the following representation, which emphasizes the fact that, if the two enol tautomers exist, they will give the same spectrum:



The keto and enol forms co-exist in equilibrium with each other, and the equilibrium point shifts with temperature. The NMR spectrum at any temperature will, of course, show features from both the keto and enol tautomers. Integration of the spectrum will allow calculation of the ratio of the two forms and hence calculation of the equilibrium constant from

$$K_X = \frac{x_{\text{enol}}}{x_{\text{keto}}} \quad 1$$

The standard state Gibbs energy for the reaction is given by

$$\Delta_r G^\circ = -RT \ln K_X \quad 2$$

The $\Delta_r H^\circ$ for the enolization can be calculated from the usual K_X versus temperature relationship,

$$\ln K_X = \frac{-\Delta_r H^\circ}{RT} + C \quad 3$$

NMR

The integrated intensity of an NMR peak is directly proportional to the number of moles of protons in that chemical environment, $n_{PA} = \text{cst } I_A$. Since we actually want the number of moles of the compound, not the number of moles of protons, the number of protons in a given chemical environment must be taken into account. For example, a methyl group has three moles of protons per mole of compound, and a methylene group has 2 moles of protons per mole of compound. Let the number of moles of protons per molecule in a given chemical environment be q . The relationship between integrated intensity and mole fractions is then:

$$x_A = \frac{n_A}{n_A + n_B} = \frac{\text{cst } I_A/q_A}{\text{cst } I_A/q_A + \text{cst } I_B/q_B} = \frac{I_A/q_A}{I_A/q_A + I_B/q_B}$$

In other words, ratios of intensities may be used directly for calculating mole fractions, because the proportionality constant cancels out.

To obtain good integral values we will use a longer pulse delay than usual. The longer delay will allow the system to return to equilibrium before the next acquisition. We will also use a smaller spectral width, to focus on the peaks of interest. A narrower spectral width will produce more data points across the peaks. The sample needs to contain some deuterated solvent for the lock system and auto-shimming to work. Therefore, even though a neat sample was studied in the literature, we will use about 20% deuterated acetone as a solvent. Acetone has the least effect on the equilibrium of any of the common solvents^{1,2}.

Pre-Laboratory

1. Predict the **qualitative** aspects of the features of the spectrum of the keto tautomer. (You will find the NMR chapter in your Physical Chemistry text helpful, as well as your Organic text. The main purpose here is to predict how many peaks should appear, whether they will be split, and where they will appear **relative** to each other. (Do not try to predict quantitative shift values.)
2. Similarly, predict the appearance of the spectrum of the enol tautomer.
3. Combine the results of 1 and 2 to predict the appearance of the overall spectrum assuming a 1:1 equilibrium of the two forms. Peak areas will be affected, of course, by the fact that this ratio will not actually be 1:1 and will change with temperature.
4. Consider which features of the spectrum might be expected to prove most valuable in determining the shifting proportions of keto to enol tautomers with temperature changes.
5. Arrange for instruction in the use of the NMR spectrometer, **before** coming to lab. Written instructions are in the instructions section at the end of the lab manual.

Procedure

1. Run the spectrum of a sample of 80% acetylacetone in 20% acetone under normal conditions. However, clear the check mark next to the Tune entry, if not already cleared (right-hand side of the window).
2. Under the Acquire Tab, in the Default H1 page, choose a reduced spectral width for your measurements, covering the features chosen for study. Check with the instructor on the appropriateness of your choice. The default spectral width, 14→-2 ppm, is too wide.

3. Set the Relaxation Delay to 10 sec to insure accurate integrals. Set the Number of Scans, to 4, to save time. Since this is a very concentrated sample, 4 FIDs will still give excellent signal to noise. Under the Start tab, clear the check marks next to the Auto Lock and Tune entries (right-hand side of the window). After the first spectrum, the system should already be locked, so avoiding the AutoTune process will save some time. Run the spectrum with the new settings. Run two replicate spectra, to estimate the uncertainty in the integral values. Record the current temperature.
4. We now need to set up the next temperature. Under the Start tab select the Spin/Temp page. In the temperature dialog box enter the next temperature and click on Regulate Temp. Return to the Start tab and make sure the check box next to Temperature is selected and the current temperature is listed in the temperature dialog box.
5. Allow 15 minutes for temperature equilibrium to be established at the new setting. Determine the spectrum and integrate at the new temperature. Run replicate spectra at each temperature to ensure that the system has reached equilibrium at the new temperature.
6. Raise the sample temperature by roughly 15° increments (stopping at 78°C), allowing ten minutes for temperature equilibrium to be established at each new setting.
7. When your samples are complete, reset the temperature to 25°C and when the temperature is equilibrated, run ethylbenzene to complete the automation run.

Calculations

1. From the peak integration, determine the ratio of the enol to the keto forms, i.e., K_X for the reaction. Remember to adjust the integrals according to the number of protons on the two forms of the molecule.
2. Make an appropriate plot for the calculation of $\Delta_r H^\circ$ and perform the calculation. Use linear least squares to obtain the best value for the slope and the uncertainty in the slope and $\Delta_r H^\circ$ and its uncertainty.
3. Calculate the Gibbs energy at each experimental temperature. From the slope and the intercept, calculate $\Delta_r G^\circ$ at 25°C. To determine the uncertainty in $\Delta_r G^\circ$ use the standard deviation of the y-values from the curve fit for the uncertainty in $\ln K_X$ (i.e. don't propagate the uncertainty in the slope and intercept to find the uncertainty in $\ln K_X$ at 25°C). Using the $\Delta_r G^\circ$ at 25°C and the $\Delta_r H^\circ$ from step 2, calculate $\Delta_r S^\circ$ for the reaction at 25°C and its uncertainty.
4. Calculate the mole % enol form at 25°C.
5. Find the literature values for the quantities calculated in 2 and 3 in Pople, Schneider, and Bernstein¹ and Allen and Dwek². Calculate your % errors from the literature values.

Discussion

Determine the approximate uncertainty in the integrals by considering replicate spectra. From the uncertainty in the integrals find the expected uncertainty in a single typical equilibrium constant near the middle of the temperature range. What is the predominant error in this overall experiment? Does this experimental error adequately account for the difference in your K_X and the literature value? Answer the following questions:

- (1). Which form is the predominate form at room temperature and why do you think this form is predominate?

- (2). Is the reaction enthalpy or entropy driven?
- (3). Does the entropy change for the reaction make sense from a molecular view point?

What is the chemical significance; why is keto-enol tautomerization important?

If you have done the “Deuterium Exchange in Keto-Enol Tautomerization” lab using GC/MS, relate these two experiments. How do deuterium exchange and thermochemical characterization complement each other?

Literature Cited

1. J. A. Pople, W. G. Schneider, and H. J. Bernstein, *High Resolution Nuclear Magnetic Resonance*, McGraw-Hill, New York, 1959. Chapter 17.
2. G. Allen and A. Dwek, *J. Chem. Soc., B*, **1966**, 161.