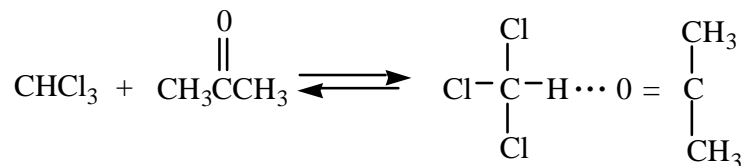
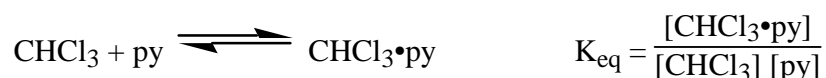


Equilibrium Constant of a Hydrogen Bonded Complex

In this experiment we will determine the equilibrium constant for the formation of the hydrogen-bonded complex between chloroform and acetone.¹



Chloroform forms complexes with a large number of Lewis bases. For example, the equilibrium constant of the complex with pyridine is rather small but still important. For :



For pyridine K_{eq} is 1.40 L/mol. These equilibria can be studied by measuring the shift of the proton resonance of chloroform upon complexation with the base. First, we must consider the appearance of the NMR spectrum of a species undergoing a rapid and reversible chemical reaction.

Effect of Fast Chemical Reactions on NMR Spectra²

We will discuss two examples of the effect of fast chemical reactions on NMR spectra; the first is the collapse of spin-spin multiplets caused by fast proton exchange and the second is the averaging of chemical shifts of protons exchanging between two different molecules.

The spectrum of ethanol is a good example of the effects of chemical reactions. The spectrum of very pure ethanol is shown in Figure 1. If one examines the spectrum of ethanol in an acidified solution, however, the result illustrated in Fig. 2 is obtained. The difference is that the spin-spin splitting from the hydroxyl proton has disappeared. Acid catalyzes a very rapid exchange of the hydroxyl proton. In the time it takes for a methylene proton to undergo resonance, many different hydrogen nuclei have been attached to the oxygen. As a result, the methylene proton experiences a field averaged to zero from the O-H nuclear moment, and the J_{HCOH} coupling disappears. In a similar fashion, the hydroxyl proton is attached to many different ethanol molecules, averaging to zero the field it experiences from $-\text{CH}_2-$ protons, and only a single resonance is observed.

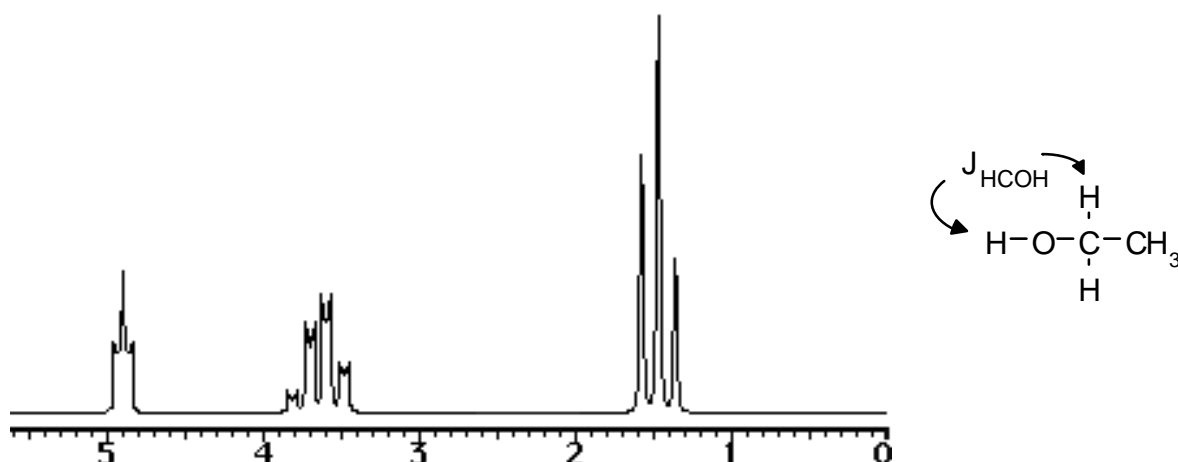


Figure 1. NMR spectrum of pure ethanol (facsimile).

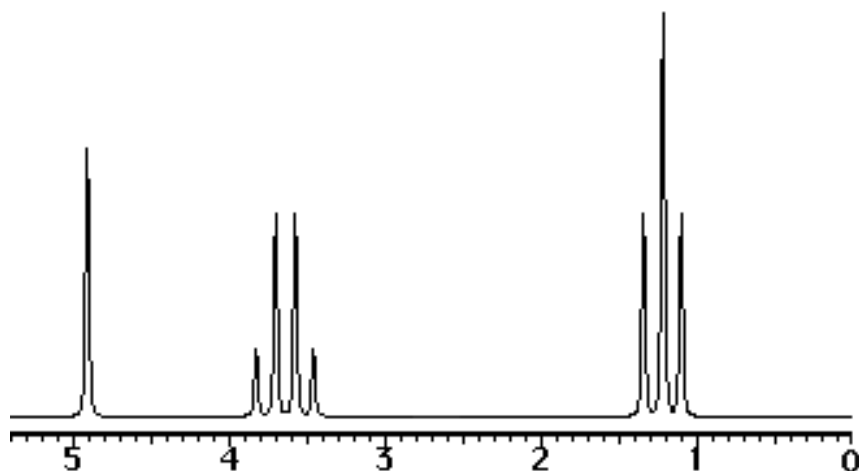


Figure 2 NMR spectrum of acidified ethanol.

This effect is called exchange narrowing. In the ethanol case the triplet of the -OH proton is narrowed to a singlet due to the collapse of the spin-spin splitting.

Exchange narrowing can also operate on systems in which protons are exchanged between sites with different chemical shifts. A very dramatic illustration of this effect is the spectrum of a solution of aqueous ammonia in which one does not see separate N-H and water O-H protons, but only a single exchange-averaged line. When exchange is rapid, the chemical shift of this exchange-averaged line is found to be a mole-fraction-weighted average of the shifts of the different types of protons being exchanged:

$$\delta_{\text{AVG}} = X_{\text{NH}} \delta_{\text{NH}_3} + X_{\text{OH}} \delta_{\text{H}_2\text{O}}$$

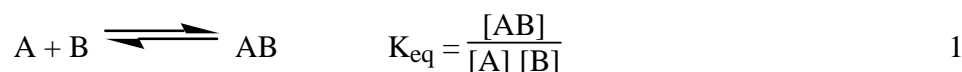
It is important to emphasize that X_{NH} is not the mole fraction of ammonia, but the mole fraction of N-H protons, i.e.,

$$X_{\text{NH}} = \frac{3 n_{\text{NH}_3}}{3 n_{\text{NH}_3} + 2 n_{\text{H}_2\text{O}}}$$

Exchange narrowing only applies if the chemical exchange is rapid. In this experiment we will be operating in this rapid exchange regime. We will use the chemical exchange weighted value of the chemical shift to derive a value for the equilibrium constant of a reaction.

Evaluation of Thermodynamic Data with NMR²

As mentioned above, when two species undergo rapid exchange on the NMR time scale, the chemical shift observed is a mole-fraction weighted average of the two resonances. Consider:



The chemical shift of the A resonance will be a mole-fraction weighted average of the resonance of the free A and that of the analogous atom in the AB adduct:

$$\delta_{\text{AVG}} = X_A \delta_A + X_{\text{AB}} \delta_{\text{AB}} \quad 2$$

where X refers to mole fraction. An analogous equation could be written for a resonance in B. Expressing Eq. 2 in molarity units:

$$\delta_{AVG} = \frac{[A]}{[A] + [AB]} \delta_A + \frac{[AB]}{[A] + [AB]} \delta_{AB} \quad 3$$

Rearranging, collecting terms, and subtracting $[AB]\delta_A$ from both sides of the equation produces:

$$[A] (\delta_{AVG} - \delta_A) + [AB] (\delta_{AVG} - \delta_A) = [AB] (\delta_{AB} - \delta_A) \quad 4$$

Define $\Delta\delta_{obs} = (\delta_{AVG} - \delta_A)$, which is the change between the observed solution chemical shift and the chemical shift of the uncomplexed molecule. Define $\Delta\delta_{CA} = (\delta_{AB} - \delta_A)$, which is the change in chemical shift between the completely complexed and uncomplexed molecule. See Figure 3 for the definition of the Δ terms.

Since the reaction has 1:1 stoichiometry:

$$[A^\circ] = [A] + [AB] \quad 5$$

where $[A^\circ]$, the initial concentration of A. Analogously for B:

$$[B^\circ] = [B] + [AB] \quad 6$$

Substituting Eq. 5, $\Delta\delta_{obs}$, and $\Delta\delta_{CA}$ into Eq. 4 gives:

$$[AB] = \frac{[A^\circ] \Delta\delta_{obs}}{\Delta\delta_{CA}} \quad 7$$

Solving for the concentrations of $[A]$ and $[B]$ and substituting Eqs. 5 and 6 into Eq. 1 gives:

$$K = \frac{[AB]}{([A^\circ] - [AB])([B^\circ] - [AB])} \quad 8$$

Next we focus on the terms in the denominator of Eq. 8. For the first term in the denominator, substituting for $[AB]$ from Eq. 7 gives:

$$([A^\circ] - [AB]) = \left([A^\circ] - \frac{[A^\circ] \Delta\delta_{obs}}{\Delta\delta_{CA}} \right) = [A^\circ] \left(\frac{\Delta\delta_{CA} - \Delta\delta_{obs}}{\Delta\delta_{CA}} \right) \quad 9$$

and for the second term in the denominator:

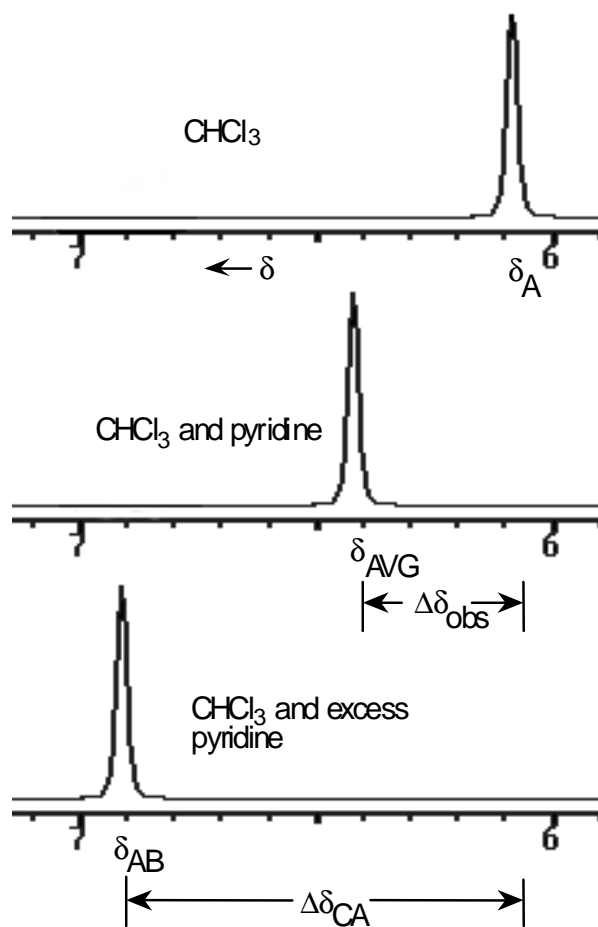


Figure 3. Shift of the chloroform resonance caused by hydrogen bonding. Top: chloroform, Middle: chloroform with intermediate concentrations of pyridine, Bottom: chloroform with a large excess of pyridine to give totally complexed chloroform.

$$([B^\circ] - [AB]) = \left([B^\circ] - \frac{[A^\circ] \Delta\delta_{\text{obs}}}{\Delta\delta_{\text{CA}}} \right) \quad 10$$

Substituting Eqs. 9 and 10 into Eq. 8 gives:

$$K = \frac{\Delta\delta_{\text{obs}}}{\left(\Delta\delta_{\text{CA}} - \Delta\delta_{\text{obs}} \right) \left([B^\circ] - \frac{[A^\circ] \Delta\delta_{\text{obs}}}{\Delta\delta_{\text{CA}}} \right)} \quad 11$$

In Eq. 11, all quantities are known except K and $\Delta\delta_{\text{CA}}$. The two unknowns are constant at a given temperature and can be obtained¹ from a series of simultaneous equations that result from measuring $\Delta\delta_{\text{obs}}$ in experiments in which $[B^\circ]$ is varied. Remember that the chemical shift of species A is being measured.

Data Analysis

For reactions with small equilibrium constants, it is not possible to shift the reaction completely towards the product complex. Therefore, $\Delta\delta_{\text{CA}}$ cannot be measured directly. But we can still recover both $\Delta\delta_{\text{CA}}$ and K by knowing $\Delta\delta_{\text{obs}}$ for different concentrations of B and non-linear curve fitting based on Eq. 11. However, Eq. 11 is not in an easy form to use in curve fitting. To make the derivation of the fit equation easier, define:

$$y \equiv \Delta\delta_{\text{obs}}/\Delta\delta_{\text{CA}} \quad 12$$

and the molar ratio of the hydrogen-bonding partners as:

$$x \equiv [B^\circ]/[A^\circ] \quad 13$$

In this experiment, A is chloroform and B is acetone. Using these definitions and Eq. 7:

$$[AB] = [A^\circ] y \quad 14$$

$$([A^\circ] - [AB]) = [A^\circ](1 - y) \quad 15$$

$$([B^\circ] - [AB]) = [A^\circ](x - y) \quad 16$$

Substitution of these three equations into Eq. 11 gives:

$$K = \frac{y}{[A^\circ](1 - y)(x - y)} \quad 17$$

For convenience define:

$$b \equiv K[A^\circ] \quad 18$$

From Eq. 17, cross-multiplying and rearranging into quadratic form gives:

$$0 = b y^2 - (1 + b(1+x)) y + bx \quad 19$$

This quadratic equation is commonly encountered in the determination of chemical equilibrium constants. Using the quadratic formula gives:

$$y = \frac{(1 + b(1+x)) \pm \sqrt{(1 + b(1+x))^2 - 4 b^2 x}}{2b} \quad 20$$

where only the negative root gives a reasonable value for y in this experiment. Substituting in the definition of y from Eq. 12, allows the fitting of $\Delta\delta_{\text{obs}}$ directly as a function of the molar ratio of the hydrogen-bonding partners, as defined in Eq. 13:

$$\Delta\delta_{\text{obs}} = \Delta\delta_{\text{CA}} \frac{(1 + b(1+x)) - \sqrt{(1 + b(1+x))^2 - 4b^2x}}{2b} \quad 21$$

Although a little messy, this equation is easily used in non-linear curve fitting. This functional form is available in the “Non-Linear Least Squares Curve Fitting” applet on the course Web site (<http://www.colby.edu/chemistry/PChem/scripts/lffitpl.html>). The applet has the corresponding functional form “ $a\{(1+b(1+x)) - \text{sqrt}[(1+b(1+x))^2 - 4(b^2)x]\}/2b + c$.” Eq. 21 doesn’t have the constant “ c ” term. The “ c ” coefficient should just be fixed as $c = 0$. Use this applet to determine K and $\Delta\delta_{\text{CA}}$. To obtain a ball-park guess for K , choose a rough guess for $\Delta\delta_{\text{CA}}$ and solve for a trial K from Eq. 11 for a typical data point.

Procedure

PreLab Assignment:

Do your calculations for preparing the solutions before coming to the laboratory.

Equipment: NMR spectrometer

1, 2, 3, 4, and 5-ml volumetric pipets
5x25-mL volumetric flasks
50-mL volumetric flask
5 nmr tubes with caps
pipet bulb
Chloroform, cyclohexane, acetone

Chloroform is a suspected carcinogen. Use gloves when handling chloroform

Procedure

Prepare a stock solution of 1.247 M chloroform and 0.2% TMS in cyclohexane by diluting 5 ml of chloroform and five drops of TMS to 50 mL in a volumetric flask. The density of chloroform is 1.489 g/ml. From this stock solution prepare a solution of 0.0998 M chloroform in cyclohexane. These concentrations result from using the standard volume pipettes listed above. This solution will give you δ_{A} .

The four remaining solutions should contain the same concentration of chloroform as this last solution and varying amounts of acetone; the concentration of acetone should be between approximately 1.0 to 2.5 M. Use 25-mL volumetrics and the volumetric pipettes listed above for these four solutions. Transfer each of the solutions to NMR tubes and cap tightly. These solutions will give you δ_{AVG} .

The instructions for using the NMR are included at the end of this manual. Remember that the chloroform is very dilute; you must increase the vertical gain in the spectral display to see it. If automatic peak listing does not find the chloroform peak, you will need to find the peaks by hand. Use cyclohexane as your chemical shift reference. So remember to measure the chemical shift of cyclohexane for each sample.

Your solutions don't contain a deuterated solvent, so you will not be able to lock the NMR or do automated shimming. Rather, make sure the NMR is tuned-up well by running a spectrum of 10% CDCl₃ in cyclohexane in the normal way.

NMR Procedure

1. Run the spectrum of a sample of 10% CDCl₃ in cyclohexane under normal conditions. However, clear the check mark next to the Tune entry to save time, if not already cleared (right-hand side of the window).
2. Set up each of your samples in the automation queue using the following settings. Leave the solvent set to CDCl₃ (even though we are working in cyclohexane, we aren't locking and shimming so the solvent information is not necessary). Under the Acquire Tab, in the Default H1 page, choose a convenient spectral width for your measurements on the features chosen for study. Check with the instructor on the appropriateness of your choice. (The default spectral width is 14→-2 ppm.) Under the Start tab, clear the check marks next to the Auto Lock, Tune, and Gradient Shim entries (right-hand side of the window).
3. Record the current temperature. The current temperature is shown in the dialog box in the lower left-hand side of the screen.
4. When your samples are complete, run ethylbenzene to complete the automation run.

If the lines in your NMR spectra become too broad, switch back to the 10% CDCl₃ in cyclohexane sample. Then continue with the rest of your samples.

Any solutions should be discarded in the waste bottle provided.

Discussion

Report the equilibrium constant for the hydrogen-bond and $\Delta\delta_{CA}$. Use the uncertainties in the fit coefficients from your non-linear curve fitting to calculate the uncertainties in K and $\Delta\delta_{CA}$. Use the correlation coefficient between the fit parameters to discuss the validity of the final results.

Is this a normal hydrogen-bond or is it unusual? Why does chloroform hydrogen bond? Calculate $\Delta_r G^\circ$ from $\Delta_r G^\circ = -RT \ln K_{eq}$. Based on your K_{eq} and $\Delta_r G^\circ$, is the hydrogen-bond strong? What is the chemical significance of this experiment? Why would you need to know this kind of information?

References

1. F.L. Slejko, R.S. Drago and D.G. Brown, *J. Amer. Chem. Soc.*, **1972**, *94*, 9210.
2. Russell S. Drago, Physical Methods in Chemistry, W.B. Saunders, Philadelphia, 1977.
3. T.F. Bolles and R.S. Drago, *J. Amer. Chem. Soc.* **1965**, *87*, 5015.