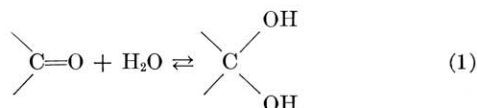


Kinetic Study by NMR

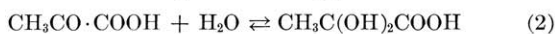
This simple nuclear magnetic resonance experiment has been devised for undergraduate students. It can be adapted easily for use with post-graduate students. The experiment provides a visual demonstration of the application of the nmr technique to chemical exchange processes.

It is well known that the carbonyl groups of certain compounds in aqueous solution form a gem-diol, i.e., a hydrate:



Confirmation of the hydrate formation of pyruvic acid has been given in several publications. Bellamy and Williams (1) have shown from the infrared spectra of solid lithium pyruvate monohydrate and lithium hydroxy pyruvate monohydrate that their structures were of the gem-diol form. Long and George (2) showed, from Raman spectra, the absence of the carbonyl group in solid lithium pyruvate monohydrate and then its presence in an aqueous solution of the salt in deuterium oxide.

The kinetics of the hydration of pyruvic acid:



to form 2,2-dihydroxypropanoic acid has been studied by a relaxation method (3). The kinetics have also been studied in detail by nmr (4). The hydration was found to be general acid-base catalyzed. Typical results which have been obtained are given below.

The proton magnetic resonance of pyruvic acid consists of two signals at 10.70 and 2.60 ppm with respect to an internal reference of tetramethylsilane. The integrated intensities of these signals are in the ratio 1:3. The carboxyl proton resonance may be assigned to the low-field signal and that of the methyl protons to the high-field signal. The proton magnetic resonance spectrum of a 4 molar solution of pyruvic acid in heavy water consists of three resonances which have chemical shifts 5.48, 2.60, and 1.75 ppm respectively. Due to fast proton exchange, the carboxyl, hydroxyl, and water protons may be assigned a single resonance, that at 5.48 ppm. The resonances at 2.60 and 1.75 ppm may be assigned to the methyl protons of pyruvic acid and 2,2 dihydroxypropanoic acid respectively.

By measuring the integrated intensities of the methyl proton resonances of the hydrate and of pyruvic acid, the equilibrium constant K_{eq} may be found:

$$K_{\text{eq}} = \frac{\text{Intensity of hydrate methyl resonance}}{\text{Intensity of pyruvic acid methyl resonance}}$$

The equilibrium constant of a 4 molar solution of pyruvic acid was found to be 0.70 at 34.5°C.

Nuclear magnetic resonance may be used to study fast exchange rates, where the mean lifetime is in the region of one second to one millisecond. It is important to impress on students that the kinetics are being obtained by nmr from a system which is in equilibrium.

A rather naive introduction to the theory of the exchange of nuclei between chemical environments may be given by the use of the Heisenberg uncertainty principle.

If nuclei of the same species exchange between two chemical environments, the two resonances of the nuclei in the two environments are observed to broaden with increase in exchange rate and finally coalesce to a single narrow resonance at very fast exchange. For the two canonically conjugate variables energy and time,

$$\Delta E \cdot \Delta t \cong \hbar \quad (3)$$

where \hbar is Planck's constant, h , divided by 2π .

But from Planck's equation relating energy and frequency

$$\Delta E = \hbar \cdot \Delta \omega \quad (4)$$

where the frequency ω is measured in radians per second. Substituting eqn. (4) into eqn. (3):

$$\Delta \omega \cong \frac{1}{\Delta t}$$

Hence, the uncertainty in the frequency (the half-width of the resonance) is approximately equal to the reciprocal of the uncertainty in the time for which the nucleus has a given energy, the mean lifetime, τ . (By the half-width of a resonance is meant its width at half its maximum amplitude.) However, nuclear magnetic resonances have a natural line width due to relaxation

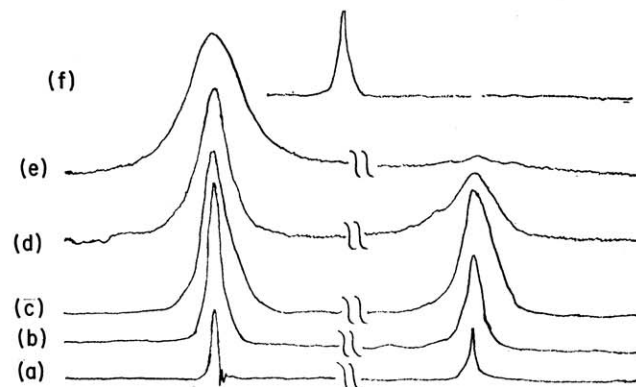


Figure 1. Proton magnetic resonance spectra of the methyl resonances of pyruvic acid and its hydrate at various acid concentrations: (a) No acid present, (b) 0.900 M HCl, (c) 1.50 M HCl, (d) 2.25 M HCl, (e) 4.5 M HCl, (f) Very high concentration of HCl.

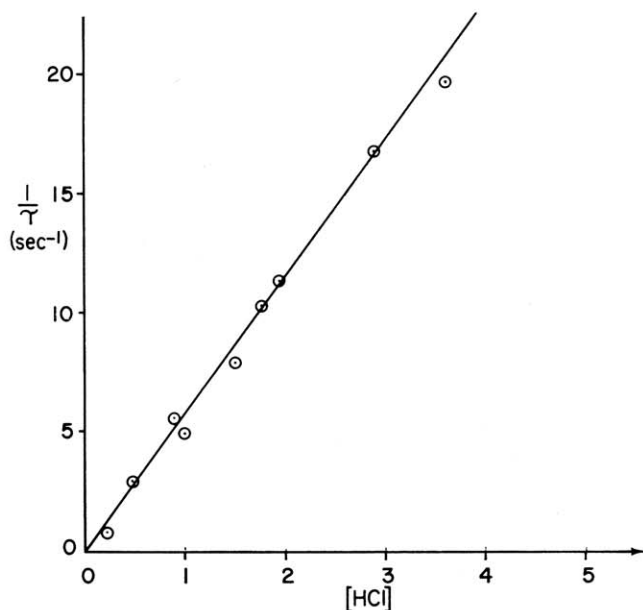


Figure 2. The reciprocal of the mean lifetime of pyruvic acid plotted against hydrochloric acid concentration.

processes, the transverse relaxation time, T_2 , being mainly responsible for the natural width of the resonance of a non-viscous liquid. Therefore, an allowance of $1/T_2$ for the natural line width must be made.

The equation can actually be shown to be:

$$\frac{\Delta\omega}{2} = \frac{1}{T_2} + \frac{1}{\tau}$$

by a more rigorous approach (5, 6).

By measuring the half-width in the absence of exchange, the transverse relaxation time may be found. The mean lifetime may now be found by measuring the half-width of the exchange-broadened resonance. For more advanced students it is possible to introduce simple computations of line shape (7, 8).

The hydration-dehydration exchange of pyruvic acid is acid catalyzed. As the exchange rate is increased by

Methyl Proton Resonances of Pyruvic Acid and its Hydrate

HCl molar conc.	Mean lifetimes (sec)	
	pyruvic acid	2,2 dihydroxy-propanoic acid
0.250	1.00	0.850
0.450	0.335	0.225
0.900	0.175	0.145
1.00	0.200	0.130
1.50	0.130	0.080
1.80	0.100	0.070
2.25	0.080	0.050
3.00	0.060	...
4.00	0.040	...

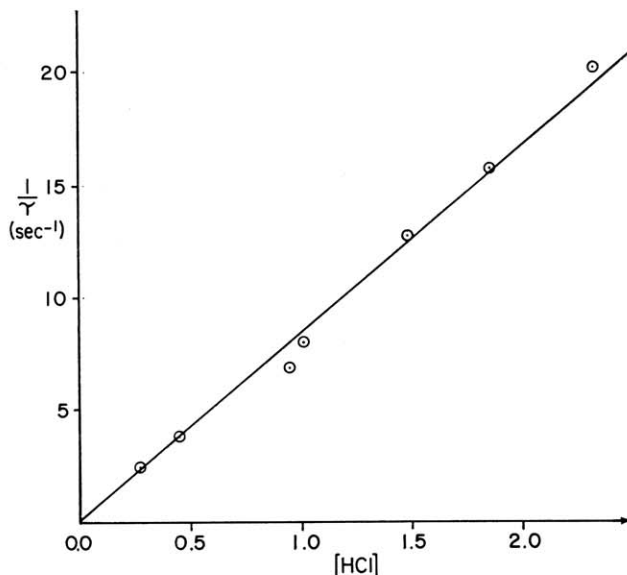


Figure 3. The reciprocal of the mean lifetime of the hydrate of pyruvic acid plotted against hydrochloric acid concentration.

the addition of hydrochloric acid, the methyl proton resonances of pyruvic acid and its hydrate are observed to broaden. With further increase in hydrochloric acid, the methyl proton resonances coalesce and finally a single narrow resonance is observed (Fig. 1). The concentration of the pyruvic acid is kept constant throughout. The methyl protons are experiencing a change in environment due to the hydration-dehydration reactions. Typical results are given in the table.

The reciprocal of the mean lifetime is equal to the specific rate of the reaction:

$$\text{specific rate} = k_{H^+}[H^+]$$

where k_{H^+} is the hydrogen ion catalytic rate constant. The reciprocals of the mean lifetimes of pyruvic acid and its hydrate are plotted against the hydrochloric acid concentration (Figs. 2 and 3 respectively) thus obtaining k_{H^+} .

The simplicity of this experiment makes it a very good demonstration of the power and techniques of nmr.

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