

A New Method for the Study of Moderately Rapid Chemical Exchange Rates Employing Nuclear Magnetic Double Resonance

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Nuclear magnetic resonance has successfully been applied in a number of studies on chemical exchange rates and the general principles of the method, which is based on the analysis of the line shapes in high resolution spectra, are well known¹⁻³. The upper limit imposed on the lifetime at any one site depends ultimately on the resolution of the spectrometer.*

However, the time constants intrinsic in the NMR method are the inverse of the natural line widths (T_1) rather than the inverse of the apparent line widths. With the innovation of the homo-nuclear double resonance method,⁴⁻⁷ a technique that does not depend on the widths and the separations in the single resonance spectra has become feasible.

To be specific, let us consider a simple two component system in which a nucleus X is rapidly transferred back and forth between two nonequivalent sites A and B. Then it is intuitively evident that an enduring retrenchment of the magnetization in site B should, because of the exchange processes, lead to a reduction of the magnetization in site A. For example, a complete saturation of the signal B should reduce the intensity of the signal A. The new equilibrium value of the z-magnetization will depend on the lifetime of X in site A (τ_A) and on the spin lattice relaxation time (T_{1A}) in site A.

If the signal B is saturated instantaneously the time dependence of the z-magnetization in site A (M_z^A) may be calculated from

* Evidently NMR can also be used as an analytical tool for measuring the relative amounts of the reacting species in slow reactions. Applied in this way the NMR method is not principally different from other physical and chemical methods and we shall not consider this type of application.

the appropriate Bloch equation modified to include chemical exchange⁸

$$\frac{dM_z^A}{dt} = \frac{M_0^A}{T_{1A}} - \frac{M_z^A}{\tau_{1A}} \quad (1)$$

where M_0^A is the initial z-magnetization of X in site A and

$$\frac{1}{\tau_{1A}} = \frac{1}{T_{1A}} + \frac{1}{\tau_A} \quad (2)$$

The solution of eqn. (1) reads

$$M_z^A = M_0^A \left(\frac{\tau_{1A}}{\tau_A} \cdot \exp(-t/\tau_{1A}) + \frac{\tau_{1A}}{T_{1A}} \right) \quad (3)$$

From a logarithmic plot of the decay curve the time constant τ_{1A} may be evaluated and the ratio τ_{1A}/T_{1A} is given by the asymptotic value of $M_z^A(t \rightarrow \infty)/M_0^A$. When a weak rf field is used to observe the NMR signal A the signal intensity is proportional to the value of M_z^A . If the inhomogeneity line widths are made large enough, one may — in a time which is short compared with τ_{1A} — make several recordings of the signal A undisturbed by "wiggles", and thus by repeatedly studying the signal intensity one may follow the decay of M_z^A .

To illustrate the present method we have studied the exchange of the hydroxyl

Table 1. Time constants evaluated from the double resonance experiments on the system of *tert*-butylalcohol (A) and 2-hydroxyacetophenone (B).

$\tau_{1A}(\text{sec})$	$\frac{\tau_{1A}}{T_{1A}}$	$\tau_{1B}(\text{sec})$	$\frac{\tau_{1B}}{T_{1B}}$
1.37	0.33	1.86	0.37
1.19	0.36	1.23	0.37
1.29	0.36	1.23	0.37
1.32	0.36	1.11	0.37
1.31	0.36	1.46	0.35
1.29	0.35	1.79	0.35
1.34	0.38	1.33	0.34
1.23	0.36	1.53	0.34
1.34	0.34	1.53	0.33
1.32	0.34	1.69	0.35
1.40	0.38	1.47	0.33
1.22	0.37	1.51	0.36
1.62	0.36		

Mean value: 1.33 0.36 1.48 0.35

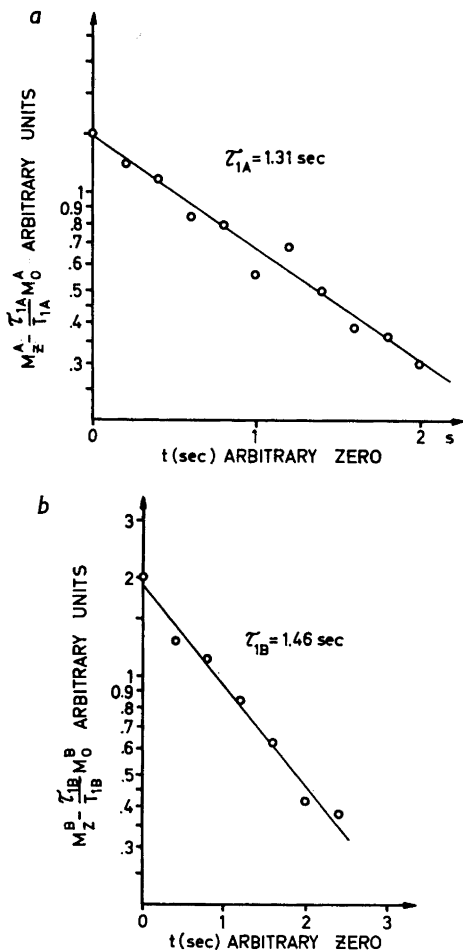


Fig. 1. Logarithmic plots of (a), the decay of the hydroxy signal of *tert*-butylalcohol (A) upon the sudden saturation of the hydroxy signal of 2-hydroxyacetophenone (B) and (b), the decay of the hydroxy signal B upon the sudden saturation of the hydroxy signal A.

protons in an equimolar mixture of *tert*-butylalcohol (A) and 2-hydroxyacetophenone (B) in a 50% carbon disulphide solution. The results are summarized in Table 1. Two representative decay curves are displayed in Figs. 1a and 1b.

From the mean values of τ_{1A} , τ_{1B} , and the quotients τ_{1A}/T_{1A} and τ_{1B}/T_{1B} the values of τ_A , T_{1A} , τ_B and T_{1B} are obtained from equation (2) and are found to be

$$\begin{array}{ll} \tau_A = 2.1 \text{ sec} & \tau_B = 2.3 \text{ sec.} \\ T_{1A} = 3.7 \text{ sec} & T_{1B} = 4.2 \text{ sec} \end{array}$$

The ratio $\tau_A/\tau_B = 0.9$ compares favourably with the ratio 1.1 of the signal intensities A/B as obtained from the integration of the single resonance spectrum.

It should be noted, that the present method provides not only the lifetimes at the two sites but also the two spin-lattice relaxation times. This is interesting, since the recovery after saturation of signals from exchangeable nuclei depends in general on more than one time constant, none of which equals the relaxation time at any one site. A more detailed discussion of the time dependence of the recoveries will be given later.

The present method may readily be generalized to cases when a nuclear spin is exchanged between several nonequivalent sites. We are presently engaged in such studies and from our preliminary results it appears that some interesting information on the mechanism of exchange may be obtained with this method.

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