York, N.Y., 1962, p 161.
(11) M. Kitamura and H. Baba, *Bull. Chem. Soc. Jpn.*, **48**, 1191 (1975).
(12) R. S. Becker, "Theory and Interpretation of Fluorescence and Phosphorescence", Wiley-Interscience, New York, N.Y., 1969, pp 156–167.

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Electronic Isotopic Substitution in Flow and Stopped Flow Nuclear Magnetic Resonance Studies of Chemical Reactions

Sir:

The techniques of flow[1-4] and stopped-flow[5,6] high resolution NMR have recently been developed and applied to the study of chemical reactions.[1-17] One of the most powerful techniques in the investigation of chemical reactions (especially rearrangements) by conventional methods has been the use of chemical isotopic substitution which enables the fate of specific atoms in the reactant molecule(s) to be traced in the transformation to product.[18] We present here a technique which enables this type of experiment to be performed for fast reactions in flowing systems using high resolution NMR without recourse to chemical substitution.

The principle of the technique is illustrated in Figures 1 and 2. In the normal continuous-flow NMR experiment, the two reactant solutions are equilibrated separately in the magnetic field, then flowed together, and the spectrum of the flowing, chemically reacting solution is recorded.[2,3] In the present experiment, the two flows are differentiated from each other by inverting or saturating some or all of the resonances of the reactant molecules in one of the two streams prior to mixing. Thus, the fate of this molecule may be traced in the products as in a chemical isotopic substitution experiment. One possible way of doing this is by use of adiabatic rapid passage (A.R.P.) techniques as illustrated in Figure 1. After magnetization, reactant stream A is passed in a continuous flow through a saturating field at the correct resonance frequency (ARP in Figure 1) before it reaches the mixing chamber. The frequency at the center of the main field is 100 MHz, that at the ARP coil ~70 MHz. In the usual ARP experiment with a stationary sample, the main magnetic field is very quickly swept through resonance.[19] In the present experiment with a flowing sample, the same net effect is achieved because of the large field gradient. Thus the molecules experience a large change in the magnetic field as they move toward the center of the gap.[20] The net effect of the ARP experiment is to completely invert the populations of the nuclear spin levels; subsequent measurement of their spectrum in the usual way at the center of the field will yield inverted signals. In this way, nuclei have been "labeled" without changing the chemical reactivity. The decay of the polarization induced by ARP back to Boltzmann equilibrium will take about three spin-lattice relaxation times; the technique will thus be best suited for the investigation of reactions which are relatively fast and will yield the initial positions of the reactant nuclei in the product(s).

The principle of the technique is illustrated in Figure 2. This shows spectra obtained from the mixing of a solution (B) of naphthalene in acetone with a solution (A) of phenol in methanol. Both solutions were equilibrated in the field and the phenol solution (A) passed through the ARP coil before entering the mixing chamber. Figure 2A shows the flow spectrum of the mixture recorded at a flow rate of 32 ml/min with the ARP power off. The small loss in resolution is due to the nonspinning flow tube and the effect of the flow itself.[1,2,20] In Figure 2B the flow is again 32 ml/min, but the ARP power is now on. The peaks due to the phenol protons have almost disappeared. Decreasing the ARP power causes an increase in these absorptions. In Figure 2C the same power level has been used but the flow rate has been increased to 58 ml/min. The degree of conversion is ~ 70%, the limiting situation for the experiment. The location of these nuclei in any subsequent reaction which might occur can now be traced.

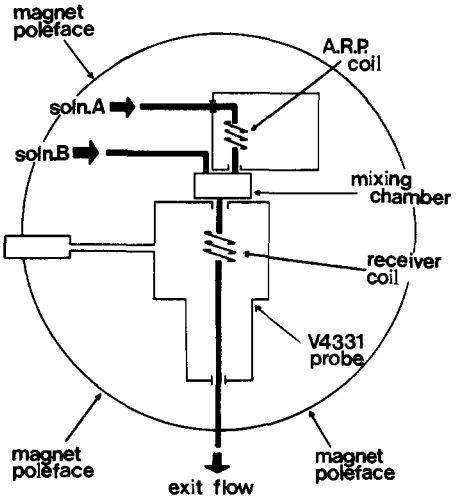

Figure 1. Schematic diagram of the equipment used to give the signal inversions described in the text.

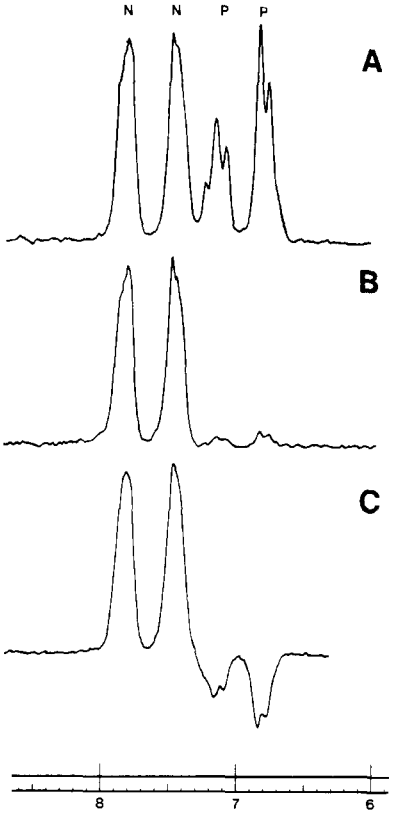

Figure 2. Flow NMR spectra of the aromatic absorptions of a mixture of phenol and naphthalene, the phenol solution passing through the ARP coil prior to mixing: (A) flow rate 32 ml/min, ARP power off; (B) flow rate 32 ml/min, ARP power on; (C) flow rate 58 ml/min, ARP power as in B.

Figure 2B illustrates another possible use of this technique; the removal of interfering peaks from a spectrum. Thus, for a given flow rate, the power may be adjusted to eliminate any given signal to zero intensity. This may even be done with solvent absorptions by inverting the solvent signal in one reactant stream and using this to cancel the positive absorption from the solvent peak in the other reactant stream giving zero

net absorption from the solvent in the mixed solution but leaving unchanged other absorptions which might have been obscured by the solvent peak.

It would be advantageous to be able to distinguish single nuclei by this method as this would in principle allow the fate of every single nucleus in the reactant to be traced to the product. This may be achieved by saturation of a single peak in the homogeneous part of the dc field at the receiver coil, followed by immediate mixing and return through this region for observation. This and other extensions and optimizations of these techniques and their application to the investigation of reaction mechanisms are currently under study in our laboratory.

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References and Notes

(1) S. W. H. Damji, Ph.D. Thesis, University of Guelph, 1975.
(2) C. A. Fyfe, M. Cocivera, S. W. H. Damji, T. A. Hostetter, D. Sproat, and J. O'Brien, *J. Magn. Reson.*, in press.
(3) J. Bargon, *Chem. Abstr.*, **76**, 92940 (1972).
(4) H. Fisher and M. Lehing, *Z. Naturforsch.*, **249**, 1771 (1969).
(5) J. Grimaldi, Jr., J. Baldo, C. McMurray, and B. D. Sykes, *J. Am. Chem. Soc.*, **94**, 7641 (1972).
(6) J. J. Grimaldi, Jr., and B. D. Sykes, *Rev. Sci. Instrum.*, **46**, 1201 (1975).
(7) C. A. Fyfe, M. Cocivera, and S. W. H. Damji, *J. Chem. Soc., Chem. Commun.*, 743 (1973).
(8) C. A. Fyfe, M. Cocivera, and S. W. H. Damji, *J. Am. Chem. Soc.*, **97**, 5707 (1975).
(9) C. A. Fyfe, S. W. H. Damji, C. D. Malkiewich, and A. R. Norris, *J. Am. Chem. Soc.*, in press.
(10) M. Cocivera, C. A. Fyfe, H. Chen, and S. Vaish, *J. Am. Chem. Soc.*, **96**, 1611 (1974).
(11) M. Cocivera, C. A. Fyfe, A. Effio, S. P. Vaish, and H. E. Chen, *J. Am. Chem. Soc.*, **98**, 1573 (1976).
(12) J. A. Richards and D. H. Evans, *Anal. Chem.*, **47**, 964 (1975).
(13) M. J. T. Robinson and S. M. Rosenfeld, *Tetrahedron Lett.*, 1431 (1975).
(14) J. J. Grimaldi and B. D. Sykes, *J. Biol. Chem.*, **250**, 1618 (1975).
(15) J. J. Grimaldi and B. D. Sykes, *J. Am. Chem. Soc.*, **97**, 273 (1975).
(16) D. A. Couch, O. W. Howarth, and P. Moore, *J. Phys. E*, **8**, 831 (1975).
(17) D. A. Couch, O. W. Howarth, and P. Moore, *J. Chem. Soc., Chem. Commun.*, 822 (1975).
(18) E. Buncel, "Reaction Mechanisms in Organic Chemistry", Vol. 9, North-Holland, Amsterdam, 1974.
(19) G. Powles *Proc. Phys. Soc., London*, **71**, 497 (1958).
(20) A. I. Zhernovol and G. D. Latyshev, "N.M.R. in a Flowing Liquid", Consultants Bureau, New York, N.Y., 1965.

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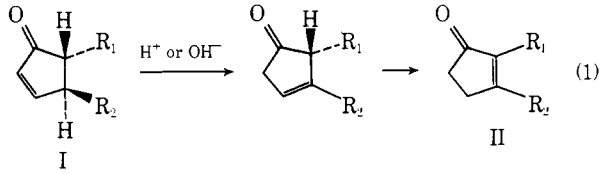
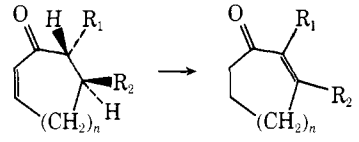
Remote Double Bond Migration via Rhodium Catalysis: A Novel Enone Transposition

Sir:

Δ^2-Cyclopentenones of type I are versatile intermediates in organic synthesis because of their ready ability to equilibrate to cyclopentenones of type II (eq 1). Isomerization of I to the more stable cyclopentenone II can be effected by heating in the presence of acid[1] or base.[2] Unlike the cyclopentenone rearrangement (eq 1) there is no analogy in cyclohexenone chemistry (e.g., III → IV (n = 1)). *In fact, there is no recorded equilibrium of cycloalkenones of type III with their corresponding (more stable) α,β-unsaturated cycloalkenones (e.g., IV) via migration of the double bond about the ring.*[3] We now report the smooth conversion of cycloalkenone III to its more stable isomer IV via rhodium catalysis which constitutes a synthetically useful new enone transposition and complements existing methods.[5]

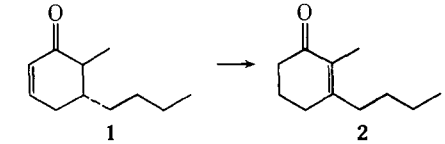


I II (1)



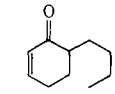
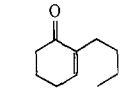
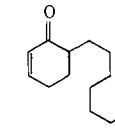
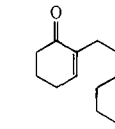
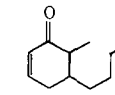
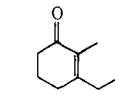
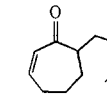
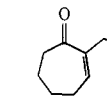
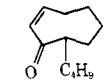
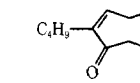
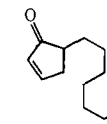
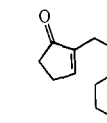
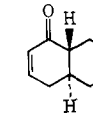
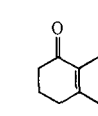
III (n = 1,2,3) IV (n = 1,2,3)

In the case of 2-methyl-3-butyl-Δ^5-cyclohexenone (**1**), isomerization to the thermodynamically more stable 2-methyl-3-butyl-Δ^2-cyclohexenone (**2**) can be carried out over



1 **2**

Table I. Enone Transposition via $RhCl_3 \cdot 3H_2O$ Catalysis[a]

Starting enone	Product	Time, h	Yield (%)[b]
		24	95[c]
		3 24	95 95
		3 24	94 91[d]
		3 24	95 91[e]
		24	80
		3 36	88 80
		12	62[f]
		24	85

[a] All reactions were carried out in a sealed tube at 100 °C containing 0.02–0.03 equiv of $RhCl_3 \cdot 3H_2O$ in absolute ethanol. [b] All yields are for isolated chromatographically pure substances. [c] Yield determined by GLC analysis. [d] Ca. 4% of the saturated ketone was isolated. [e] Ca. 6% of the saturated ketone was isolated. [f] Ca. 31% of the saturated ketone was isolated.