The Use of Nuclear Magnetic Double Resonance to Study Reversible Intramolecular Processes

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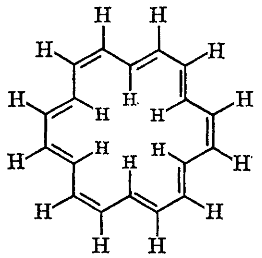
WE report the use of nuclear magnetic double resonance to detect proton exchange between non-equivalent sites in a slow reversible intramolecular process.

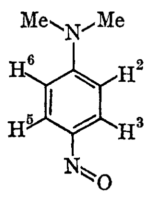
The n.m.r. spectrum[1] of [18]annulene (I)[2] in perdeuterotoluene at 100° shows a single band at τ 4·5. On cooling, the band broadens, disappears at *ca.* 50°, and at 20° two new broad signals have appeared at τ 13·0 and 1·2 (Figure 1a). On further cooling these bands are resolved, and at −60°

appear as a high-field quintet (τ 14·22, 6 inner protons) and a low-field quartet (τ 0·75, 12 outer protons).[3]

When the high-field absorption band of (I) is irradiated at −60°, in a double irradiation frequency-swept experiment, the low-field quartet collapses to a singlet. Under the same conditions, irradiation of the low-field absorption band causes the collapse of the high-field signal to a broad singlet. However, when these experiments are performed at 20°, the absorption due to the non-irradiated signal completely disappears (Figures 1b, c).[4] At temperatures between 20° and −60°, effects intermediate between these extremes are observed; as the temperature is lowered, the non-irradiated signal appears as a decoupled singlet, the intensity of which increases with decreasing temperature. These observations are due to the transfer of an irradiated inner proton to the position of an outer proton, or an irradiated outer proton to the position of an inner proton, before spin relaxation has completely occurred.



(I)



(II)

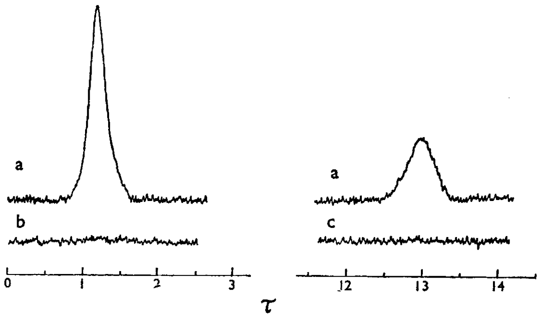


FIGURE 1: *The* ^{1}H *resonance frequency-swept spectrum of* [18]*annulene in* $C_6D_5CD_3$ *at* 20°.

(*a*) *With no double irradiation.*

(*b*) *With strong irradiation at the high-field frequency.*

(*c*) *With strong irradiation at the low-field frequency.*

N.m.r. studies of the hindered internal rotation of *p*-nitrosodimethylaniline (II) have been reported.[5,6] We have investigated the effect of double irradiation on this compound.

In perdeuteroacetone, at −60°, the spectrum of the aromatic protons of (II) consists of a low-field doublet (τ 1·12, H^3), and a double doublet (τ 3·07, H^2) and a multiplet (τ 3·39, H^5, H^6) at higher field.[5] At −60°, normal decoupling occurs, and the observed changes in the spectrum support the above assignments. Figure 2a shows the spectrum of the aromatic protons of (II) at −20°.[7] Irradiation at the frequency of the H^5, H^6 absorption causes the disappearance of the low-field (H^3) band (Figure 2b). Irradiation at the frequency of the H^3 absorption causes the virtual disappearance of *all* of the H^2, H^5, H^6 signals (Figure 2c). Since rotation of the nitroso-group converts H^3 into H^5, irradiation at the frequency of the H^3 absorption leads to the saturation of the H^5 signal. As H^5 and H^6 have almost identical chemical shifts and are strongly coupled ($J_{5,6}$ = 9·1 c./sec.),[5] saturation of H^5 will lead to saturation of H^6 due to spin–spin interaction.[8] The rotation of the nitroso-group interconverts H^2 and H^6, and thus saturation of H^6 is equivalent to saturation of H^2. Hence, provided that the rate of rotation of the nitroso-group is faster than the relaxation process, irradiation at the frequency of the low-field proton absorption will lead to disappearance of the high-field aromatic resonance.

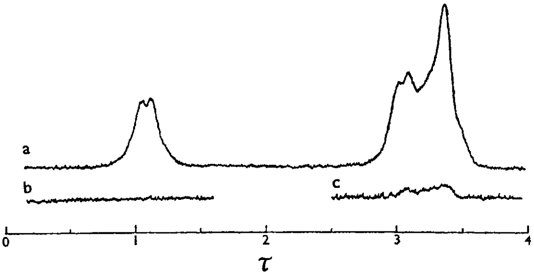


FIGURE 2: *The* ^{1}H *resonance frequency-swept spectrum of* p-*nitrosodimethylaniline in* $(CD_3)_2CO$ *at* −20°.

(a) *With no double irradiation.*

(b) *With strong irradiation at the* H^5,H^6 *frequency.*

(c) *With strong irradiation at the* H^3 *frequency.*

In deuterochloroform, at −60°, the spectrum of the aromatic protons of (II) consists of a low-field double doublet (τ 1·19, H^3), and a multiplet (τ 3·25, H^2, H^5) and a double doublet (τ 3·55, H^6) at higher field.[6] At $-60°$, normal decoupling again occurs, and the changes in the spectrum support the above assignments. Figure 3a shows the spectrum of the aromatic protons of (II) at $-20°$.[7] Irradiation at the frequency of the H^2, H^5 absorption causes the disappearance of the low-field (H^3) band (Figure 3b). Irradiation at the H^3 frequency approximately halves the intensity of the H^2, H^5 band, but leaves the H^6 signal essentially unchanged (Figure 3c). Rotation of the nitroso-group converts H^3 into H^5, and thus irradiation at the frequency of the H^3 absorption leads to the saturation of the H^5 proton signal. In this case, however, H^5 and H^6 do not have nearly identical chemical shifts, and therefore saturation of H^5 does not lead to saturation of H^6. The H^5 and H^2 protons do have nearly identical chemical shifts, but the spin–spin interaction is small ($J_{2,5} = 0$ c./sec.),[5] and hence saturation of H^5 does not result in saturation of the H^2 resonance. Irradiation at the position of the low-field absorption will thus only result in the removal of the H^5 signal.

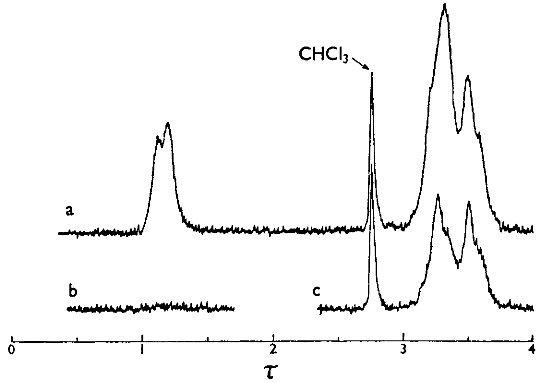


FIGURE 3: *The* ^{1}H *resonance frequency-swept spectrum of* p-*nitrosodimethylaniline in* $CDCl_3$ *at* $-20°$.

(a) *With no double irradiation.*

(b) *With strong irradiation at the* H^2, H^5 *frequency.*

(c) *With strong irradiation at the* H^3 *frequency.*

Double-irradiation experiments on substituted [18]annulenes[9] suggest that spin–spin interaction of protons with nearly identical chemical shifts is an important factor in the disappearance of the non-irradiated signals in these compounds, and thus probably in [18]annulene itself.

The presently described *intramolecular* exchange phenomena are comparable to the recently described *intermolecular* processes.[10] The double-irradiation technique should provide an additional method for the investigation of slow reversible intramolecular processes between nonequivalent sites. The method, of course, is difficult to apply in those cases in which the chemical-shift difference of the protons in the two environments is small (*e.g.*, ring inversion in saturated six-membered rings).[11]

(*Received, November* 23*rd,* 1966; *Com.* 923.)

[1] All n.m.r. spectra were recorded at 100 Mc./sec. under conditions of frequency sweep, tetramethylsilane being used as an internal standard.

[2] F. Sondheimer, R. Wolovsky, and Y. Amiel, *J. Amer. Chem. Soc.*, 1962, **84**, 274; L. M. Jackman, F. Sondheimer, Y. Amiel, D. A. Ben-Efraim, Y. Gaoni, R. Wolovsky, and A. A. Bothner-By, *ibid.*, p. 4307; Y. Gaoni, A. Melera, F. Sondheimer, and R. Wolovsky, *Proc. Chem. Soc.*, 1964, 397; F. Sondheimer, *Proc. Roy. Soc. A.*, in the press; F. Sondheimer, I. C. Calder, J. A. Elix, Y. Gaoni, P. J. Garratt, K. Grohmann, G. Di Maio, J. Mayer, M. V. Sargent, and R. Wolovsky, *Chem. Soc. Special Publ.*, in the press.

[3] An upfield shift of *ca.* τ 1·2 of the signal due to the inner protons was observed on changing the solvent from perdeuterotetrahydrofuran (ref. 2) to perdeuterotoluene.

[4] The intensities of the proton signals due to the residual non-deuterated toluene were unaffected.

[5] D. D. MacNicol, R. Wallace, and J. C. D. Brand, *Trans. Faraday Soc.*, 1956, **61**, 1.

[6] P. K. Korver, P. J. van der Haak, and T. J. de Boer, *Tetrahedron*, 1966, **22**, 3157.

[7] At this temperature the bands were less well resolved than at $-60°$ (see refs. 5, 6).

[8] J. W. Emsley, J. Feeney, and L. H. Sutcliffe, "High Resolution Nuclear Magnetic Resonance Spectroscopy", Pergamon Press, Oxford, 1965, Vol. 1, p. 29.

[9] I. C. Calder, P. J. Garratt, H. C. Louguet-Higgins, F. Sondheimer, and R. Wolovsky, *J. Chem. Soc.* (*C*), in the press.

[10] J. Feeney and A. Heinrich, *Chem. Comm.*, 1966, 295.

[11] We have examined cyclohexyl bromide (ref. 12) and *N*-methylmorpholine (ref. 13); effects similar to those described occur, but these cases are less well defined.

[12] W. C. Neikam and B. P. Dailey, *J. Chem. Phys.*, 1963, **38**, 445.

[13] R. K. Harris and R. A. Spragg, *Chem. Comm.*, 1966, 314.