tional absorption is due to the BrO_2 radical which has an absorption maximum at 480 nm.[17]

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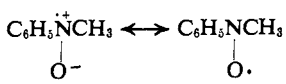
Proton Magnetic Resonance Emission in the Intramolecular Rearrangement of a Tertiary Amine Oxide

Sir:

Several recent studies[1-3] present evidence for a radical nitrogen to oxygen group migration in the thermal Meisenheimer rearrangement[4] of amine oxides. At temperatures 40° below that required for a significant rate of rearrangement, steady-state N-methyl-N-phenylnitroxyl radical (I) concentrations were clearly charac-



I

terized by esr measurements on solutions of N-methyl-N-benzylaniline oxide.[1] I may not actually participate in the rearrangement since very slow O-substituted product formation occurs under these conditions and no benzyl radicals were detected. However, under rearrangement conditions the effect of *para* substituents in either the benzyl[1] or phenyl[2] rings is very small (ρ $\sim$0.9), as would be expected in a radical process. Oxygen trapping even at high pressure reduced the product by only two-thirds.[3] Thus a nonradical route[4] or a caged radical pair[3] has been postulated to account for the untrapped rearrangement product. Evidence for radical pair participation in rearrangement processes can also be obtained by proton magnetic resonance (pmr) emission and enhanced absorption in reaction products.[5] We have now used pmr emission to obtain direct evidence for both nitroxyl and benzyl radicals in the rearrangement of a tertiary amine oxide.

The pmr spectrum of N,N-dimethylbenzylamine oxide (II)[6] was scanned during thermal rearrangement at 130–155°.[8] In the region δ 2.0–5.2 ppm (Figure 1),

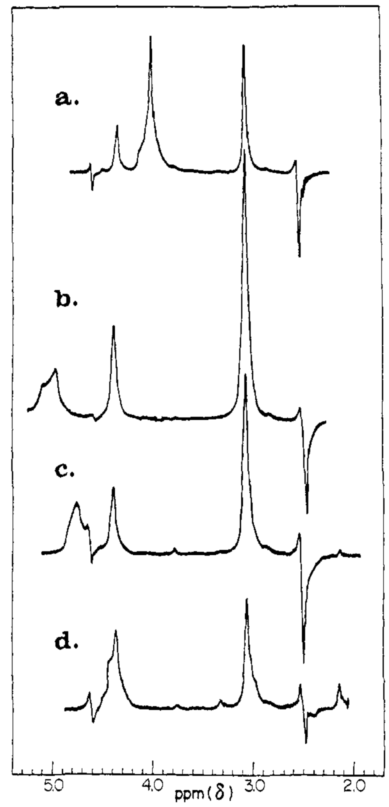


Figure 1. Proton magnetic resonance spectra of the emission-active region in the N,N-dimethylbenzylamine oxide (II) layer (lower phase of two phase system) during thermal conversion to N,N-dimethyl-O-benzylhydroxylamine (III): (a) scan started 3.9 min after placing a concentrated aqueous solution of II in the probe at 148°; (b–d) scans started 0.4, 4.5, and 10.0 min after placing the crystalline monohydrate of II in the probe at 130°.

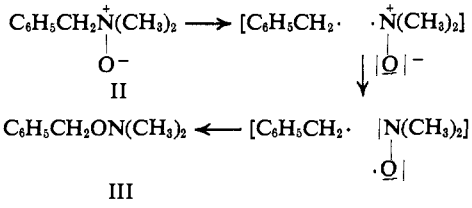
emission singlets were observed at δ 2.5 and 4.6 ppm.[9] These signals, from the methyl and methylene protons, respectively, in the rearrangement product N,N-dimethyl-O-benzylhydroxylamine (III) are respectively upfield and downfield from the comparable singlets of II. Aqueous solutions from vacuum concentration of the amine oxide preparation after destruction of hydrogen peroxide have generally been used[7,10,11] in producing III by thermolysis of II. A pmr scan, started 3.9 min after placing such a solution in the preheated (148°) probe, had a strong water peak centered at 4.0 ppm (Figure 1a). This solution had measurable emission for more than 50 min. Since preparative rearrangement is carried out at elevated temperatures (85–165°[7,10,11]) under vacuum, water evaporates rapidly during this reaction. Pmr measurements under these conditions were not viable; therefore we sought to remove all water by freeze drying the material at 0.01 Torr. The hygroscopic free flowing white powder, mp 63–66°, obtained in this fashion was found (pmr in $CDCl_3$) to be a monohydrate with a bound water peak at 5.03 ppm. When the neat solid is heated to 130°, the water peak gradually shifts from slightly

(1) U. Schöllkopf, U. Ludwig, M. Patsch, and W. Franken, *Ann.*, 703, 77 (1967).
(2) U. Schöllkopf and U. Ludwig, *Chem. Ber.*, **101**, 2224 (1968).
(3) J. P. Lorand, R. W. Grant, P. A. Samuel, E. O'Connel, and J. Zero, 158th National Meeting of the American Chemical Society, New York, N. Y., Sept 1969, Abstracts ORGN 125; *Tetrahedron Lett.*, 4087 (1969).
(4) R. A. W. Johnstone in "Mechanisms of Molecular Migrations," Vol. 2, B. S. Thyagarajan, Ed., Interscience Publishers, New York, N. Y., 1969, p 249.
(5) A. R. Lepley, *J. Amer. Chem. Soc.*, **91**, 1237 (1969); J. E. Baldwin and J. E. Brown, *ibid.*, **91**, 3647 (1969); U. Schöllkopf, *et al.*, *Tetrahedron Lett.*, 2619, 3415 (1969).
(6) Prepared as described in ref 7.
(7) U. Schöllkopf and H. Schäfer, *Ann.*, **683**, 42 (1965).
(8) Temperatures are based on ethylene glycol standardization at the same controller settings. Spectra presented were recorded on a Varian A 56-60A at the University of Utah; all other studies were made with a Varian A-60A spectrometer at Marshall University. At the temperatures necessary for rearrangement, boiling of the aqueous amine oxide may cause erratic pmr signals.

(9) Peak shifts of −0.07 and −0.05 ppm, respectively, were noted when the moisture content of the sample was minimized. All peaks are assigned relative to the 3.06 ppm methyl singlet of II as measured at 26° as a 20% solution in $CDCl_3$ with 1% $(CH_3)_4Si$.
(10) A. C. Cope and P. H. Towle, *J. Amer. Chem. Soc.*, **71**, 3423 (1949).
(11) G. P. Schulman, P. Ellgen, and M. Conner, *Can. J. Chem.*, **43**, 3459 (1965).

downfield of this location (Figure 1b) toward the upfield position (Figure 1c, d) of an aqueous II solution (Figure 1a). This water shift is directly related to the conversion of II into III. III is less dense than II and insoluble in it. Thus a second phase rapidly forms as rearrangement takes place; III, which does not hydrate, separates above the oxide layer which builds up water from the reacted monohydrate. The upper layer gives a normal pmr absorption spectrum of III since the bulk of the material has undergone nuclear spin relaxation, while the lower layer shows emission as long as conversion remains rapid[12] since most of the III in this layer has just been formed under conditions of nuclear polarization. Thus, if protracted emission is to be observed, care must be taken to position the sample tube so that the detector coil is measuring the lower phase at all times. Although III is the predominant product, some reduction of II occurs, as is evident from the slow appearance of the weak methyl and methylene absorption singlets of N,N-dimethylbenzylamine at δ 2.14 and 3.33 ppm, respectively (Figure 1c and d).

The emission signals from both the methylene and methyl groups of III represent both the migrating and terminus moieties, respectively, involved in the rearrangement process. Since unpaired electron precursors are necessary to build up the abnormal nuclear spin state distributions resulting in pmr emission,[5] emission from both moieties is direct evidence for homolytic bond formation from a radical pair. If thermal homolytic cleavage of the weak CN bond between benzyl and the charged nitrogen of II precedes formation of a



III

CO bond in the electron-redistributed radical pair, a reaction route is provided which accounts for the observed emission. The positive entropy (7.9 ± 2.5 cal/deg) and low enthalpy (34.2 ± 1 kcal) of activation measured[11] for this reaction are appropriate for this type of process. In addition, Closs and Closs have suggested[13] for pairwise-generated radicals that emission will only be evident in recombinations occurring within the cage of initial formation. Thus only the part of the rearrangement which could not be trapped by oxygen[3] would be directly detected by nmr techniques. The oxygen trapping of I[3] and the comparable 60–80% racemization at methylene (CHD) in conversion of II to III[6] would then agree with the amount of escape from the cage.

In addition to furnishing direct evidence for a radical pair in the Meisenheimer rearrangement, the current study is unique in reporting emission from methyl groups which do not directly participate in the migrations. Proton emission from a migrating benzyl methylene and a methyne terminus have been reported in a Stevens rearrangement of a quaternary ammonium reaction intermediate.[14] However the current emission adjacent to the point of bond cleavage is an indication that protons both α and β to migration sites may act as pmr polarization probes for homolytic rearrangement processes.

Acknowledgment. The authors are indebted to Dr. J. P. Lorand for providing the results of his studies prior to publication and to Professor C. Walling for helpful discussions.

(12) After about three-fourths of the crystalline oxide has reacted, 15 min at 130°, and the water peak has shifted three-fourths of the distance toward that shown in Figure 1a, emission changes to weak absorption unless the temperature is increased significantly, *e.g.*, 148–155°.

(13) G. L. Closs and L. E. Closs, *J. Amer. Chem. Soc.*, **91**, 4550 (1969).

(14) A. R. Lepley, *Amer. Chem. Soc., Div. Petrol. Chem.*, **14**, No. 2, C43 (1969).

(15) On leave from Marshall University.

(16) Undergraduate research participant, summer 1969.

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Experiments Leading to the Elucidation of the Purine Proton Magnetic Resonance Line Broadening upon Purine Intercalation in Single-Stranded Nucleic Acids

Sir:

When purine is added to aqueous solutions of single-stranded nucleic acids, *e.g.*, dinucleoside monophosphates,[1] or polyuridylic acid (poly U),[2] it has been shown that a purine-intercalated complex is formed which involves sandwiching of a purine molecule between adjacent bases of the dinucleotide or polynucleotide. This complexation has been monitored through the effect of the intercalated purine on the chemical shifts of the base protons of the nucleic acid,[1-5] and by conformational changes in the ribose phosphate backbone reflected by changes in the vicinal coupling constant between the $H_{1'}$ and $H_{2'}$ ribose protons.[3] The purine proton resonances are also appreciably broadened, particularly at low purine/nucleotide ratios where the fraction of incorporated to unbound purine is high.[1,2] The three purine proton resonances are not equally broadened, with the H_6 and H_8 resonances affected to a considerably greater extent than the H_2 resonance. Chan, *et al.*,[1] have proposed that the purine protons experience a strong dipolar field when the purine base is incorporated between the adjacent bases of the dinucleotide segment and the purine proton resonances are broadened by nuclear spin relaxation induced by fluctuations of these local dipolar fields. In particular, it was proposed that the greater part of the dipolar field arises from the $H_{2'}$, $H_{3'}$, $H_{5'}$, $H_{5''}$ ribose protons, which are situated around the bend of the "U" on the inner side of the cage when the conformation of the dinucleotide segment corresponds to that for maximum interaction of the nucleic acid bases with the incorporated purine base.

(1) S. I. Chan, B. W. Bangerter, and H. H. Peter, *Proc. Nat. Acad. Sci. U. S.*, **55**, 720 (1966).

(2) B. W. Bangerter and S. I. Chan, *Biopolymers*, **6**, 983 (1968).

(3) S. I. Chan and J. H. Nelson, *J. Amer. Chem. Soc.*, **91**, 168 (1969).

(4) J. H. Nelson, Ph.D. Thesis, California Institute of Technology, 1968.

(5) B. W. Bangerter, Ph.D. Thesis, California Institute of Technology, 1968.