Electron Paramagnetic Resonance Studies of Unstable Free Radicals in the Reaction of t-Butyl Hydroperoxides and Alkylamines

BY G. M. COPPINGER AND J. D. SWALEN

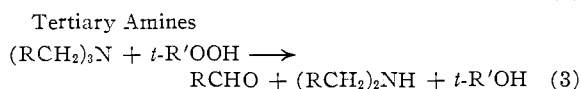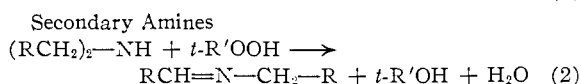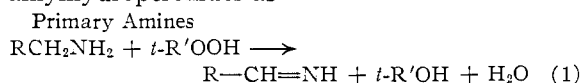The reaction between t-butyl hydroperoxide and a number of alkyl amines has been studied using the technique of electron paramagnetic resonance. A previously undetected radical species, an amine oxide free radical, has been observed in these reactions. Its probable structure has been determined to be R·R'—CH—NO·—CHR'·R. The implications of this free radical species are discussed in relation to the reaction mechanism as previously suggested by De La Mare. The probable electronic properties of this free radical species are described.

Introduction

Electron paramagnetic resonance (e.p.r.) techniques have been applied in the study of the reactions of alkyl amines and t-butyl hydroperoxide. De La Mare[1,2] has examined these reactions rather extensively and has postulated that they involve a free radical mechanism, at least in part. There are, however, some anomalies in the experimental observations and results. We undertook an e.p.r. study of these systems in the hope that additional information could partially clarify the results of the classical organic chemical approaches.

Alkylhydroperoxides are reduced by amines to the corresponding alcohol. The oxidation products from the amines are somewhat different depending upon whether the amine is primary, secondary or tertiary. The products are representative of a greater part of amine chemistry; secondary reactions are possible and the complexity of such secondary reactions always restricts a complete material balance. Nevertheless, it is possible to describe the reactions of amines and t-alkylhydroperoxides as
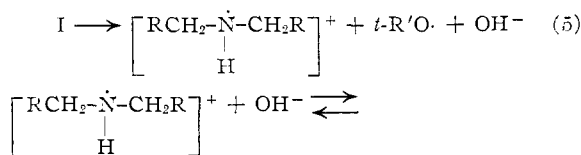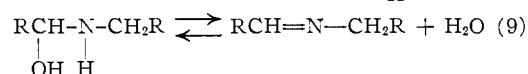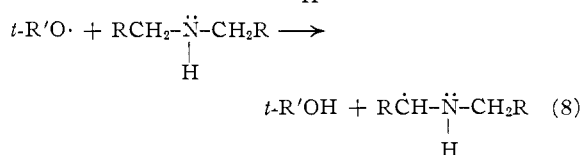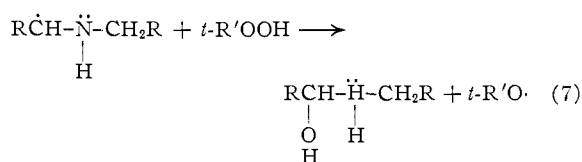
Primary Amines
$$RCH_2NH_2 + t\text{-}R'OOH \longrightarrow$$
$$R\text{—}CH\text{=}NH + t\text{-}R'OH + H_2O \quad (1)$$

Secondary Amines
$$(RCH_2)_2\text{—}NH + t\text{-}R'OOH \longrightarrow$$
$$RCH\text{=}N\text{—}CH_2\text{—}R + t\text{-}R'OH + H_2O \quad (2)$$

Tertiary Amines
$$(RCH_2)_3N + t\text{-}R'OOH \longrightarrow$$
$$RCHO + (RCH_2)_2NH + t\text{-}R'OH \quad (3)$$

The oxidation–reduction reaction is preceded by an acid–base equilibrium reaction

$$(RCH_2)_2NH + t\text{-}R'OOH \rightleftharpoons$$
$$[(RCH_2)_2NH\text{—}t\text{-}R'OOH] \quad (4)$$
$$(I)$$
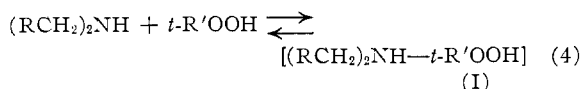
The rate of disappearance of hydroperoxide is slower in the presence of oxygen or oxidation inhibitors, a characteristic of a free radical process.

De La Mare originally suggested that these observations could be explained by the free radical chain reactions

$$I \longrightarrow \left[\underset{\overset{|}{H}}{RCH_2\text{-}\overset{\cdot}{N}\text{-}CH_2R} \right]^{+} + t\text{-}R'O\cdot + OH^{-} \quad (5)$$

$$\left[\underset{\overset{|}{H}}{RCH_2\text{-}\overset{\cdot}{N}\text{-}CH_2R} \right]^{+} + OH^{-} \rightleftharpoons$$

(1) H. E. De La Mare, J. Org. Chem., 25, 2114 (1960).
(2) C. W. Capp and E. G. E. Hawkins, J. Chem. Soc., 4106 (1953).

$$\underset{\overset{|}{H}}{R\overset{\cdot}{C}H\text{-}\overset{\cdot\cdot}{N}\text{-}CH_2R} + H_2O \longleftrightarrow \underset{\overset{|}{H}}{R\overset{\cdot}{C}H\text{-}\overset{\cdot}{N}\text{-}CH_2R} \quad (6)$$

$$\underset{\overset{|}{H}}{R\overset{\cdot}{C}H\text{-}\overset{\cdot\cdot}{N}\text{-}CH_2R} + t\text{-}R'OOH \longrightarrow$$
$$\underset{\overset{|}{O}\ \overset{|}{H}}{\underset{H}{RCH\text{-}\overset{\cdot\cdot}{H}\text{-}CH_2R}} + t\text{-}R'O\cdot \quad (7)$$

$$t\text{-}R'O\cdot + \underset{\overset{|}{H}}{RCH_2\text{-}\overset{\cdot\cdot}{N}\text{-}CH_2R} \longrightarrow$$
$$t\text{-}R'OH + \underset{\overset{|}{H}}{R\overset{\cdot}{C}H\text{-}\overset{\cdot\cdot}{N}\text{-}CH_2R} \quad (8)$$

$$\underset{\overset{|}{OH}\ \overset{|}{H}}{RCH\text{-}N\text{-}CH_2R} \rightleftharpoons RCH\text{=}N\text{—}CH_2R + H_2O \quad (9)$$

We undertook the examination of this reaction by e.p.r. techniques in order to detect these postulated free radical intermediates and to determine their structure. None of the species suggested in the above reaction sequence was detected. Instead free radical species derived from N-oxides were observed in eleven di- and tri-alkylamine reactions. The general structure of these free radical species is

$$\left[\underset{\overset{|}{O}}{R\text{-}N\text{-}R} \right]\cdot \quad (II)$$
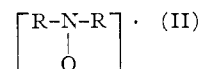
Interpretation of the Spectra.—A first order calculation of the energy levels was adequate to account satisfactorily for all the spectra. The corresponding energy levels are

$$W/2\beta = \tfrac{1}{2}gH_zS_z + A_N S_z I_{Nz} + \sum_i A_{Hi} S_z I_{Hzi} \quad (10)$$

where only the z components of the various spin angular momenta are included. Very little effect of the second order terms was noted. Hence they have been neglected. In Table I the results based on eq. 10 for the various radicals are given to the accuracy of ±0.5 gauss. All the spectra had a g value of 2.0038 ± 0.0005, indicating that the electron is very close to the free electron spin value.

The nuclear spin–electron spin coupling terms give us some information about the electronic wave function and the molecular structure of the free radical. The Fermi term A has the form

$$\frac{16\pi}{3} g_I \mu_N \beta \psi^2(0) \overrightarrow{I} \cdot \overrightarrow{S} \quad (11)$$

where g_I is the nuclear g value, μ_N is the nuclear

magneton, $\psi^2(0)$ is the electron density at the nucleus. This constant A is therefore proportional to the electron spin density at the various nuclei of the molecule. Since a p orbital and all other higher orbitals have a node at the nuclei, only the s orbitals interact. The Fermi term therefore measures the amount of s character of the free electron wave function and gives the electron localization at the various positions in the molecule. Usually the free electron is in a pπ orbital and through configuration interaction some s character is introduced.

The free electron is spin coupled with the nitrogen nucleus and with the α carbon protons but not with the protons of the R groups (diphenylamine is a different system and a different splitting pattern occurs). The N^{14} nucleus ($I = 1$) splits the line into three lines of equal intensity. The four protons split the lines further into five lines with intensity ratios which follow the binomial coefficients (1:4:6:4:1). Since all the di-*n*-alkyl radicals have about the same spectral constants, we conclude that the free radicals have almost identical structures. The di-isopropyl and di-*sec*-butyl radicals have only two protons and therefore each nitrogen line is split into a 1:2:1 triplet. The smaller proton splitting would indicate a change in bonding which most probably involves an angular change and hence a slightly different hybridization.

The spectra observed from di-*n*-propylamine and from di-benzylamine were identical with the spectra obtained from di-*n*-propylhydroxylamine and from dibenzylhydroxylamine, respectively. We conclude that we are probably observing the same free radical whether formed from amine or hydroxylamine.

In each of the reactions only a single distinct free radical species was observed with a concentration of about 10^{-3} to 10^{-5} M. Any other free radicals present must be down in concentration by at least a factor of 10.

A lower limit for the life-time of the observed free radicals can be estimated from the widths of the absorption lines. We obtained a value somewhat greater than 10^{-6} second, but unfortunately this information is of little help since the radicals certainly exist much longer than this. A very simple alternative measurement was made by reducing the temperature and observing the decay of the resonance signal. The signal decayed as rapidly as the temperature was lowered: from 10^{-3} to $<10^{-6}$ M when the temperature was reduced from 80 to 20° in approximately 15 seconds. Whether one concludes that the life-time is a few seconds or a few milliseconds, it is clear that the observed free radicals were unstable and that measurements were made on a steady state concentration. *This means that the spectra are characteristic of a reacting system rather than a static system.*

Electronic and Molecular Structure.—A number of nitrogen-containing free radicals have been studied by paramagnetic resonance, by optical pumping and by microwave spectroscopy. The results of this work are summarized in Table II.

Dousmanis[4] has estimated $\psi^2(0)$ to have a value of 34×10^{24} cm.$^{-3}$ for a 2s electron on the nitrogen atom. The ratio of the derived value of $\psi^2(0)$ in Table II to the value 34×10^{24} cm.$^{-3}$ gives to an order of magnitude the amount of 2s character in the free electron's wave function.

TABLE I

SPECTRAL PARAMETERS IN THE E.P.R. SPECTRA OF FREE RADICALS PRODUCED IN THE REACTION OF AMINES AND HYDROXYLAMINES WITH *t*-BUTYL HYDROPEROXIDE

Compound	A_N(Gauss)	A_H(Gauss)	No. of lines
Diethylamine	15.5	10.6	15
Di-*n*-propylamine	15.5	10.6	15
Di-*n*-propylhydroxylamine	15.7	10.5	15
Di-*n*-butylamine	15.7	10.5	15
Di-isopropylamine	16.0	4.7	9
Di-*sec*-butylamine	15.4	4.1	9
Dibenzylamine	15.6	9.5	15
Dibenzylhydroxylamine	15.6	9.1	15
Piperidine	17.4	11.7	15
Diallylamine	15.5	9.3	15
Diphenylamine	10.5	0.9	33
Tri-*n*-propylamine	15.7	10.5	15
Tri-*n*-butylamine	15.7	10.5	15

TABLE II

E.P.R. NITROGEN PARAMETERS FOR RELATED FREE RADICALS

Compound	A_N(Gauss)	$\psi^2(0)$	Lit.
N	3.7	0.23×10^{24} cm.$^{-3}$	5, 6
NH$_2$	10.3	.62	7
NO	14.2	.85	4
NO$_2$	107	6.3	8
$\begin{bmatrix} SO_3-N-SO_3 \\ \mid \\ O\cdot \end{bmatrix}^-$	13	0.78	9
$C_6H_5-NO_2\cdot$	11.1	0.66	10

In Table III the hydrogen contact terms are given for a number of compounds. In radicals of hydrocarbons a $\sigma-\pi$ interaction causes the splitting

TABLE III

E.P.R. PROTON PARAMETERS FOR RELATED FREE RADICALS

Compound	A_H(Gauss)		Lit.
NH$_2$	23.9		7
CH$_3$	25		11–13
CH$_3$CH$_2$	27.1,	22.5	14
CH$_3$CHCH$_3$	25		13

of the resonances by the various protons. It is interesting that the methyl splitting in the ethyl radicals is greater than the methylene splitting

(3) A. Abragam and M. H. L. Pryce, *Proc. Roy. Soc. (London)*, **A205**, 135 (1951); see also D. J. E. Ingram, "Free Radicals as Studied by Electron Spin Resonance," Butterworths, London, 1958.

(4) G. C. Dousmanis, *Phys. Rev.*, **97**, 967 (1955).

(5) M. A. Heald and R. Beringer, *Phys. Rev.*, **96**, 645 (1954).

(6) W. W. Holloway and R. Novick, *Phys. Rev. Ltrs.*, **1**, 367 (1958).

(7) S. N. Foner, E. L. Cochran, V. A. Bowers and C. H. Jen, *ibid.*, **1**, 91 (1958).

(8) G. R. Bird, J. C. Baird and R. B. Williams, *J. Chem. Phys.*, **28**, 738 (1958).

(9) G. E. Pake, J. Townsend and S. I. Weissman, *Phys. Rev.*, **85**, 682 (1952).

(10) R. L. Ward, *J. Chem. Phys.*, **30**, 852 (1959).

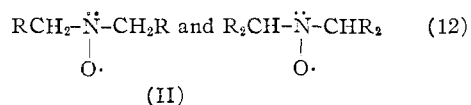(11) C. F. Luck and W. Gordy, *J. Am. Chem. Soc.*, **78**, 3240 (1956).

(12) W. Gordy and C. G. McCormick, *ibid.*, **78**, 3243 (1956).

(13) B. Smaller and M. S. Matheson, *J. Chem. Phys.*, **28**, 1169 (1958).

27.1 and 22.5 gauss, respectively.[14] Although the methyl group is farther way, the sp³ hybridization contains some 2pπ admixture which interacts with the radical more than the orthogonal sp² hybridization on the same carbon atom. Since the NH₂ radical has about the same proton constant as the CH₃, it is postulated that the protons on the α carbons in the amine radicals like the isopropyl radical should have about the same value of the Fermi constant. The observed values of 15 to 17 gauss are, however, smaller than the predicted value of 23 to 26 gauss. This indicates that the free electron in the radicals probably is not localized as much on the nitrogen atom.

A comparison of the nitrogen splitting given in Table II is more ambiguous. Dousmanis[4] estimated that the free electron is about 60% on the nitrogen atom in NO and about 40% on the oxygen atom. This would be consistent with our observation for the proton splitting and for the nitrogen splitting in our free radicals. The free radical $\left[SO_3\text{-}\overset{..}{N}\text{-}SO_3\right]^-$ is also in agreement with the

amine radicals reported here (see Tables I and II); therefore the electronic structures probably are very similar.

On the basis of the results given in Tables II and III, we should expect an amine radical to have a nitrogen splitting around 10 to 12 gauss and a proton splitting around 23 to 26 gauss, and we should expect an amine oxide radical to have a nitrogen splitting around 13 to 16 gauss and a proton splitting around 11 to 15 gauss. Although this does not constitute a proof for the structure, it certainly indicates that the amine oxide structure is more probable.

$$RCH_2\text{-}\overset{..}{N}\text{-}CH_2R \quad \text{and} \quad R_2CH\text{-}\overset{..}{N}\text{-}CHR_2 \quad (12)$$
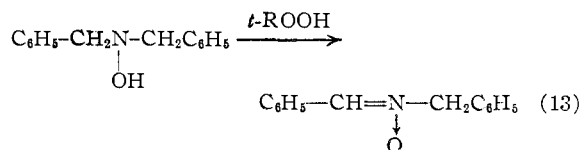$$\overset{|}{O\cdot} \qquad\qquad \overset{|}{O\cdot}$$
$$(II)$$

Discussion of Results

The free radical species II cannot arise from a side reaction because, assuming an upper limit of one second for radical life-time, the total amount of this free radical species over the course of the reaction is in each case closely equivalent to the total amine oxidized. On the other hand, the free radical species II cannot be a unique intermediate in the oxidation of amines, for then the final products would be nitrones and not imines. The same free radical species II is observed in the oxidation of both amines and hydroxylamines. De La Mare[15] has determined that the product of oxidation of dibenzylhydroxylamine is quite clearly

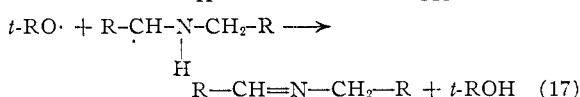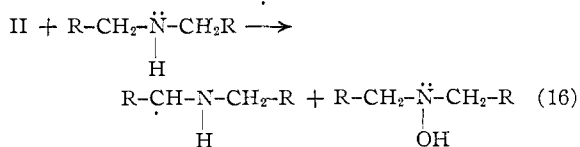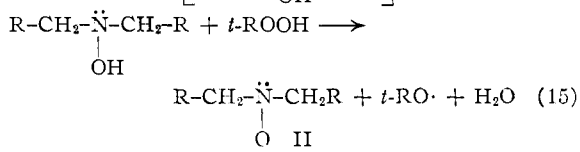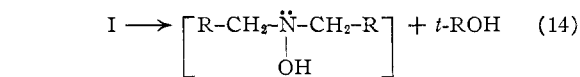(14) R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, **33**, 935 (1960).

(15) H. E. De La Mare, private communication.

$$C_6H_5\text{-}CH_2\overset{|}{N}\text{-}CH_2C_6H_5 \xrightarrow{\textit{t}\text{-ROOH}}$$
$$\overset{|}{OH}$$

$$C_6H_5\text{---}CH\text{=}N\text{---}CH_2C_6H_5 \quad (13)$$
$$\overset{\downarrow}{O}$$

However, nitrones cannot be more than minor products from the oxidation of the amines examined.

These points lead us to conclude that only a small fraction of amine is oxidized to the free radical species II, probably through initial formation of hydroxylamine. The free radical species II takes part in chain transfer steps to produce other free radicals which in turn oxidize amine to imine. The chain transfer steps involving II must number at least two in order that a steady state concentration of II be maintained.

As a result of these findings, De La Mare[1] has proposed the alternative reaction mechanism

$$I \longrightarrow \left[R\text{-}CH_2\text{-}\overset{..}{N}\text{-}CH_2\text{-}R\right] + \textit{t}\text{-}ROH \quad (14)$$
$$\overset{|}{OH}$$

$$R\text{-}CH_2\text{-}\overset{..}{N}\text{-}CH_2\text{-}R + \textit{t}\text{-}ROOH \longrightarrow$$
$$\overset{|}{OH}$$

$$R\text{-}CH_2\text{-}\overset{..}{N}\text{-}CH_2R + \textit{t}\text{-}RO\cdot + H_2O \quad (15)$$
$$\overset{|}{O} \quad II$$

$$II + R\text{-}CH_2\text{-}\overset{..}{N}\text{-}CH_2R \longrightarrow$$
$$\overset{|}{H}$$

$$R\text{-}CH\text{-}N\text{-}CH_2\text{-}R + R\text{-}CH_2\text{-}\overset{..}{N}\text{-}CH_2\text{-}R \quad (16)$$
$$\overset{|}{H} \qquad\qquad\qquad \overset{|}{OH}$$

$$\textit{t}\text{-}RO\cdot + R\text{-}CH\text{-}N\text{-}CH_2\text{-}R \longrightarrow$$
$$\overset{|}{H}$$
$$R\text{---}CH\text{=}N\text{---}CH_2\text{---}R + \textit{t}\text{-}ROH \quad (17)$$

In conclusion, the amine free radical species determined very likely plays a dominant role in the oxidation of amines to imines by *t*-butylhydroperoxide.

Experimental

The e.p.r. measurements were made on the Varian EPR spectrometer V 4500. In this particular case the magnetic field was swept about 70 gauss in order to cover all the lines. A magnetic modulation of about 2 gauss at a frequency of 200 c.p.s. was used. A quartz cylinder about 7 mm. o.d. was inserted at the node line of the cavity and served to conduct the heated nitrogen gas. The samples were mounted inside this cylinder in open and sealed tubes which were blanketed with the stream of heated nitrogen gas. The temperature of the samples varied from 30 to 80°. Many times an induction period of up to a half an hour was observed before the spectra appeared. Detection of radicals from amines required a longer induction period than from hydroxylamine. The ratio of the reactants varied from 1:3 to 3:1, but this variation produced only a slight effect: small variations in intensity of the e.p.r. absorption were observed. Benzene was used as a solvent for the solid amines and hydroxylamines, but also some of the liquid systems were diluted with benzene. No difference was noted compared with the undiluted reaction systems.