701. *Electron Spin Resonance Studies of Oxidation. Part II.*[1]
Aliphatic Acids and Substituted Acids.

By W. T. Dixon, R. O. C. Norman, and (in part) A. L. Buley.

The electron spin resonance spectra of the radicals formed by the reaction of the hydroxyl radical, generated from titanous ion and hydrogen peroxide in acid solution, with aliphatic acids, α-chloro-acids, α-hydroxy-acids, αβ-unsaturated acids, and a number of other aliphatic compounds are reported. Conclusions are drawn about the courses of the reactions; the activating or deactivating effects of substituents on the ease of abstraction, by ·OH, of hydrogen from C–H; stabilising influences in the radicals so formed; and the variation in the coupling constants of protons in different environments. Particular attention is given to the dependence of the coupling of C_2-protons on the conformation of the radicals.

WE have shown previously that the electron spin resonance (e.s.r.) spectra of short-lived organic radicals can be observed by mixing acidified solutions of titanous ion and hydrogen peroxide, in the presence of organic compounds, immediately before they flow into an aqueous cell in the cavity of the spectrometer.[1] Evidence was presented that the primary reaction is the one-electron reduction of the peroxide by titanous ion to give the hydroxyl radical, which then reacts with the organic compound. Attention was confined in Part I to the reactions of aliphatic alcohols, and it was shown that the technique both enables conclusions to be drawn about the mode of reaction of organic compounds with the hydroxyl radical and makes possible a systematic investigation of the variation in the magnitude of the coupling constants of protons in different environments with the un-paired electron in the radical. In the latter context the advantage of studying these radicals in solution instead of by solid-state techniques was stressed.

We now report results for a number of other aliphatic compounds, with particular reference to acids, α-chloro-acids, α-hydroxy-acids, and unsaturated acids. The data obtained for these compounds, together with the radicals to which the spectra are assigned, are set out in Table 1. Some of the more interesting spectra are reproduced in Figs. 1—6.

Abstraction from Saturated Compounds.—(a) *Acids.* Whereas the presence of an alcohol in approximately 0·1M-concentration caused the complete disappearance of the signal ascribed to ·OH, a similar concentration of acetic acid made little difference to this spectrum. When the concentration of acid was increased, however, the amplitude of the singlet decreased and there appeared with increasing intensity a spectrum consisting of a triplet together with a weaker quartet (Fig. 1). Finally, at a concentration of acetic acid ≥2M, the singlet was entirely eliminated.

[1] Part I, Dixon and Norman, *J.*, 1963, 3119.

TABLE 1.

Spectra and coupling constants of radicals derived from acids, and the radicals to which the spectra are assigned.

Acid	Type of spectrum	C_1–H	C_2–H	C_3–H	OH	Radical
$CH_3 \cdot CO_2H$	Triplet (1:2:1) and	21·8				$\cdot CH_2 \cdot CO_2H \cdot$
	weak quartet (1:3:3:1)	23·1				$\cdot CH_3$
$CH_2(CO_2H)_2$	Triplet (1:2:1)	21·7				$\cdot CH_2 \cdot CO_2H$
$(CH_3)_3C \cdot CO_2H$	Triplet (1:2:1) of septets (1:6:15:20:15:6:1)[a]	21·8				$\cdot CH_2 \cdot C(CH_3)_2 \cdot CO_2H$
$CH_3 \cdot CH_2 \cdot CO_2H$	Triplet (1:2:1) of triplets (1:2:1)[b]	22·4	26·6	0·7		$\cdot CH_2 \cdot CH_2 \cdot CO_2H$
$CH_2Cl \cdot CO_2H$	Two (1:1) quartets (1:1:1:1)[b]	20·9				$\cdot CHCl \cdot CO_2H$
$CH_3 \cdot CHCl \cdot CO_2H$	Quartet (1:3:3:1) of quartets (1:1:1:1)[c]	20·9				$\cdot CCl(CH_3) \cdot CO_2H$
$CHCl_2 \cdot CO_2H$	Septet (1:2:3:4:3:2:1)[d]					$\cdot CCl_2 \cdot CO_2H$
$H \cdot CO_2H$	Singlet					$\cdot CO_2H$ or $H \cdot CO_2 \cdot$
$CH_2(OH) \cdot CO_2H$	Two (1:1) doublets (1:1)	17·8			2·6	$\cdot CH(OH) \cdot CO_2H$
$CH_3 \cdot CH(OH) \cdot CO_2H$	Two (1:1) quartets (1:3:3:1)		17·1		2·0	$\cdot C(OH)CH_3 \cdot CO_2H$
$CO_2H \cdot CH_2 \cdot CH(OH) \cdot CO_2H$	Two (1:1) triplets (1:2:1)		10·0		2·0	$\cdot C(OH)(CO_2H) \cdot CH_2 \cdot CO_2H$
$CO_2H \cdot CH(OH) \cdot CH(OH) \cdot CO_2H$	Two (1:1) doublets (1:1)		3·9		1·6	$\cdot C(OH)(CO_2H) \cdot CH(OH) \cdot CO_2H$
$CO_2H \cdot CH=CH \cdot CO_2H$	Two (1:1) doublets[a]	21·1	12·7			$\cdot CH(CO_2H) \cdot CH(OH) \cdot CO_2H$
$CH_3 \cdot CH=CH \cdot CO_2H$	Four quartets (1:3:3:1)[a]	22·0	25·8[e] 16·3[f]			$\cdot CH(CH_3) \cdot CH(OH) \cdot CO_2H$

[a] The assignments of these coupling constants are discussed in the text. [b,c,d] Coupling with chlorine nuclei: [b] 3·8, [c] 2·6, [d] 3·1 gauss. [e] Quartet. [f] Doublet.

View Online

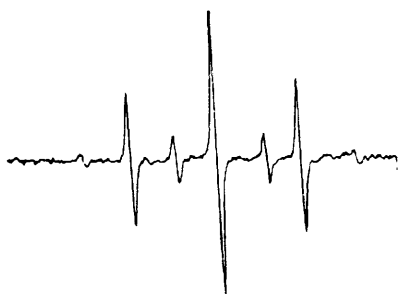[1964] *Electron Spin Resonance Studies of Oxidation. Part II.* 3627

FIG. 1. Spectrum from acetic acid.

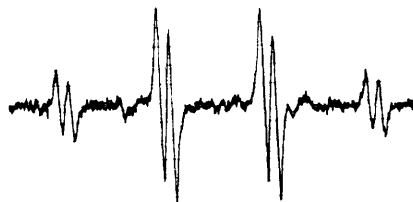FIG. 2. Spectrum from chloroacetic acid.
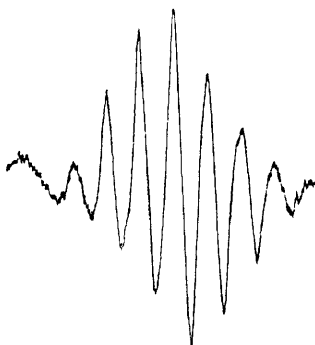
FIG. 4. Spectrum from lactic acid.

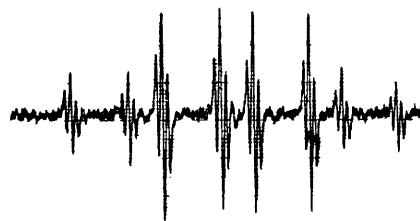FIG. 3. Spectrum from chloral hydrate.

FIG. 5. Spectrum from diethyl ether.

FIG. 6. Spectrum from cyclobutane-1,1-dicarboxylic acid.

The triplet (coupling constant, 21·8 G) is ascribed to $\cdot CH_2 \cdot CO_2H$, for which coupling constants of 21 [2] and 20·4 G [3] have been reported previously. The quartet is the spectrum characteristic of the methyl radical,[1] and it is concluded that methyl radicals are formed by the abstraction of a hydrogen atom from the carboxyl group of acetic acid, followed by decarboxylation [4] of the acetoxy-radical:

$$CH_3 \cdot CO_2H + \cdot OH \longrightarrow CH_3 \cdot C(=O)O\cdot + H_2O \qquad (1)$$
$$CH_3 \cdot C(=O)O\cdot \longrightarrow \cdot CH_3 + CO_2 \qquad (2)$$

[2] Weiner and Koski, *J. Amer. Chem. Soc.*, 1963, **85**, 873.
[3] Horsfield, Morton, and Whiffen, *Mol. Phys.*, 1961, **4**, 328.
[4] Walling, " Free Radicals in Solution," John Wiley and Sons, New York, 1957, p. 491.

There was no indication of a spectrum which could be attributed to the acetoxy-radical (which should appear either as a singlet or as a quartet of much narrower splitting than the spectrum of $\cdot CH_3$), and this is consistent with the view that reactions (1) and (2) are essentially simultaneous.[5]

Malonic acid was less reactive than acetic acid, but at concentrations >2M the signal due to $\cdot OH$ was eliminated and the spectrum consisted of a triplet (1 : 2 : 1) whose coupling constant was the same, within experimental error, as that of the triplet derived from acetic acid which was assigned to $\cdot CH_2 \cdot CO_2H$. It is therefore probable that this same radical was present, formed analogously to the methyl radical from acetic acid:

$$CO_2H \cdot CH_2 \cdot CO_2H \xrightarrow{\cdot OH} CO_2H \cdot CH_2 \cdot CO_2 \cdot \longrightarrow CO_2H \cdot CH_2 \cdot + CO_2 \qquad (3)$$
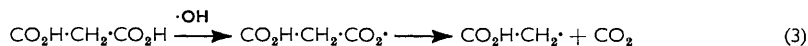
The $\cdot OH$ singlet was eliminated by a smaller concentration of propionic acid than was required by acetic acid. The spectrum obtained was too complex for complete analysis, but its strongest lines constituted a triplet of triplets, and this spectrum may be assigned with reasonable confidence to $\cdot CH_2 \cdot CH_2 \cdot CO_2H$, formed by abstraction of a β-hydrogen atom. As expected, this spectrum differs from that of the isomeric radical, $\cdot CH(CH_3) \cdot CO_2H$, obtained by γ-irradiation of a single crystal of L-alanine.[6]

Pivalic acid in 0·1M concentration caused the complete replacement of the $\cdot OH$ signal and the appearance of an intense spectrum which consisted of a triplet of septets similar to that obtained from t-butyl alcohol.[1] This is ascribed to $\cdot CH_2 \cdot C(CH_3)_2 \cdot CO_2H$ and represents another example of the occurrence of weak splitting by C_3-protons.[1]

Formic acid gave a singlet of width about 2 G (cf. ref. 7) situated about 5 G upfield from the $\cdot OH$ singlet. This may be the spectrum of either $H \cdot CO_2 \cdot$ or $\cdot CO_2H$.

(*b*) α-*Chloro-acids.* Chloroacetic acid was more reactive than acetic acid and only a 0·2M solution was necessary for complete replacement of the $\cdot OH$ signal. The resulting spectrum (Fig. 2), near $g = 2$, consisted of two quartets, each line being of the same intensity, indicative of coupling with ^{35}Cl and ^{37}Cl nuclei in the radical $\cdot CHCl \cdot CO_2H$.

Dichloroacetic acid was much less reactive and the $\cdot OH$ signal was not eliminated even at molar concentration. The resulting spectrum, similar to that obtained from chloral hydrate (Fig. 3) but less intense and partly obscured by the residual $\cdot OH$ singlet, was a septet of pattern approximately 1 : 2 : 3 : 4 : 3 : 2 : 1, as expected for $\cdot CCl_2 \cdot CO_2H$.

α-Chloropropionic acid gave a comparatively simple spectrum consisting of a basic quartet each of whose lines was resolved into four. This is attributed to $\cdot CCl(CH_3) \cdot CO_2H$, and shows that α-abstraction is dominant over β-abstraction. The origin of some less intense lines was not clear, but by analogy with propionic acid some abstraction from the β-position would be expected.

(*c*) α-*Hydroxy-acids.* The α-hydroxy-acids examined were all more reactive than the corresponding unsubstituted acids and 0·1M solutions were sufficient to cause the complete disappearance of the $\cdot OH$ signal. The spectra given by lactic acid (Fig. 4) and malic acid are assigned to the radicals $\cdot C(OH)(CH_3) \cdot CO_2H$ and $\cdot C(OH)(CH_2 \cdot CO_2H) \cdot CO_2H$, respectively, which are produced on the abstraction of α-hydrogen atoms; these results indicate that the hydroxyl group activates the adjacent C–H bond towards reaction with $\cdot OH$, as suggested previously,[1] and as expected by analogy with the products formed by α-hydroxy-acids with Fenton's reagent which behaves similarly to the titanous–peroxide system.*

---

* It has been shown that the two systems behave similarly in the hydroxylation of benzenoid compounds.[8] Although free radicals are not detectable when titanous ion is replaced by ferrous ion in the strongly acidic conditions used in the present work and previously,[1] they are detectable with buffered solutions *ca.* pH 6 in the presence of EDTA.[9]

[5] Rembaum and Szwarc, *J. Amer. Chem. Soc.*, 1955, **77**, 3486.
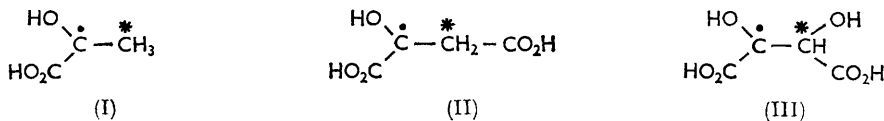[6] Horsfield, Morton, and Whiffen, *Mol. Phys.*, 1961, **4**, 425.
[7] Ovenall and Whiffen, *Mol. Phys.*, 1961, **4**, 135.
[8] Lindsay Smith and Norman, *J.*, 1963, 2897.
[9] Buley and Norman, unpublished observations.

Two features of the spectra derived from α-hydroxy-acids are of particular interest. First, the narrow doublet splitting of each line (*e.g.*, Fig. 4) shows that there is weak coupling between the unpaired electron and the proton of the hydroxyl group, as has previously been observed in the spectrum of $\cdot CH(OH)\cdot CO_2H$, derived from the γ-irradiation of a single crystal of glycollic acid.[10] We did not observe such coupling in the spectra from alcohols with the exception of propargyl alcohol, although in the case of the triplet from methanol each line was apparently an incompletely resolved doublet,[1] and the present results prompted a re-examination of some of the alcohols. The lines in the spectrum from methanol were eventually resolved into narrowly spaced doublets (coupling constant, 1 G), but those from the other alcohols could not be resolved further.

Secondly, the coupling constants of C_2-protons vary in a dramatic manner with the nature of the substituents on this carbon atom, as shown by the following series:

$$
\begin{array}{ccc}
\underset{\text{HO}_2\text{C}}{\overset{\text{HO}}{>}}\overset{\bullet\quad *}{\text{C}}-\text{CH}_3 & \underset{\text{HO}_2\text{C}}{\overset{\text{HO}}{>}}\overset{\bullet\quad *}{\text{C}}-\text{CH}_2-\text{CO}_2\text{H} & \underset{\text{HO}_2\text{C}}{\overset{\text{HO}}{>}}\overset{\bullet\quad *}{\text{C}}-\underset{\text{CO}_2\text{H}}{\overset{\text{OH}}{\text{CH}}}
\end{array}
$$

(I) (II) (III)

* Coupling constant (gauss) (I) 17·1; (II) 10·1; (III) 3·9.

The implications of these results are discussed below.

Finally, the spectrum from malic acid contained a weak signal whose lines were sufficiently displaced from those of the main spectrum for two doublets to be discerned. This pattern is the same as that obtained from maleic and fumaric acids and is probably therefore due to the same radical (IV), formed in this case by abstraction of a β-hydrogen atom.

(*d*) *Unsaturated acids.* Acrylic acid gave a complex spectrum with misshapen lines which appeared to result from the overlapping of several absorptions. It is probable that polymerisation occurred and that the observed spectrum was due to a mixture of a number of the resulting radicals.

Maleic acid and fumaric acid behaved similarly, giving the same spectrum of two doublets, assigned to the adduct (IV) of the hydroxyl radical and the double bond. Addition has been observed previously with allyl alcohol.[1]

$$
\begin{array}{cc}
\underset{\text{HO}_2\text{C}}{\overset{\text{H}}{>}}\overset{\bullet}{\text{C}}-\underset{\text{CO}_2\text{H}}{\overset{\text{OH}}{\text{CH}}} \quad \text{(IV)} & \underset{\text{H}_3\text{C}}{\overset{\text{H}}{>}}\overset{\bullet}{\text{C}}-\underset{\text{CO}_2\text{H}}{\overset{\text{OH}}{\text{CH}}} \quad \text{(V)}
\end{array}
$$

Crotonic acid behaved similarly in that the main spectrum consisted of four quartets as expected for (V). Other, less intense lines were present, possibly due to radicals formed by the addition of $\cdot OH$ to the other end of the double bond or by the abstraction of hydrogen from the methyl group.
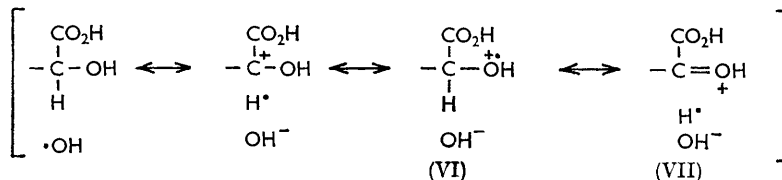
(*e*) *Other acids.* The following acids gave spectra which could not be analysed because of their complexity: butyric, isobutyric, succinic and citric. Bromo-, dibromo-, trichloro-, iodo-, and cyano-acetic acids and glycine did not react perceptibly under the conditions employed.

The Reactivity of C–H *Bonds.*—The results above show that acids are considerably less reactive than alcohols towards $\cdot OH$; that two carboxyl groups have a greater deactivating influence than one; and that abstraction of hydrogen occurs preferentially at the carbon atom furthest from carboxyl (*e.g.*, in propionic acid). On the other hand, α-hydroxy-acids are more reactive than their unsubstituted analogues and abstraction occurs preferentially from the α-carbon atom.

[10] Atherton and Whiffen, *Mol. Phys.*, 1960, **3**, 1, 103.

These facts are consistent with the view which has been expressed previously that the hydroxyl radical has electrophilic character.[1,11] With acids, the $-I$ effect of the carboxyl group deactivates each C–H bond towards attack by the electrophilic radical, the extent of deactivation decreasing as the C–H bond is further removed from carboxyl. In this respect, the results parallel those observed in the free-radical chlorination of aliphatic acids by the electrophilic chlorine atom: for example, propionic acid is more readily substituted at the β- than at the α-carbon.[12] With α-hydroxy-acids, however, the more powerful deactivating effect of carboxyl at the α- than at the β-carbon is evidently more than offset by the mesomeric effect of the hydroxylic oxygen, which serves to lower the energy of the transition state for abstraction from the α-position, as expressed by the contribution of the canonical structures (VI) and (VII):

Transition state:

$$
\left[
\begin{array}{cccc}
\mathrm{CO_2H} & \mathrm{CO_2H} & \mathrm{CO_2H} & \mathrm{CO_2H} \\
-\overset{|}{\underset{|}{C}}-\mathrm{OH} \longleftrightarrow & -\overset{|+}{C}-\mathrm{OH} \longleftrightarrow & -\overset{|}{C}-\overset{+\bullet}{\mathrm{OH}} \longleftrightarrow & -\overset{|}{C}=\underset{+}{\mathrm{OH}} \\
\mathrm{H} & \mathrm{H}^{\bullet} & \mathrm{H} & \mathrm{H}^{\bullet} \\
\bullet\mathrm{OH} & \mathrm{OH}^{-} & \mathrm{OH}^{-} & \mathrm{OH}^{-} \\
 & & \text{(VI)} & \text{(VII)}
\end{array}
\right]
$$

Chloroacetic acid reacted more readily than acetic acid and this implies a stabilising effect by chlorine in the transition state analogous to that by oxygen. The lack of re-activity of bromoacetic acid and iodoacetic acid may derive from the smaller $+M$ effects of these substituents, while the lower reactivity of dichloroacetic acid than of chloroacetic acid may be the result either of steric hindrance or of the combined effect of two $-I$ substituents outweighing the $+M$ effect.

To examine further the electrophilic behaviour of ·OH, the reactions of a number of ethers, amines, aldehydes, and ketones were studied. The results for those compounds which gave spectra that could be analysed are recorded in Table 2.

First, to confirm that the activating power of the hydroxyl group in the abstraction of hydrogen by ·OH lies in the hydroxyl group itself and not in the oxyanion group (which should scarcely be present in significant concentration in the strongly acid condition), we examined three ethers. Diethyl ether gave a spectrum (Fig. 3) very similar to that from ethanol save that each line was split into a triplet. This spectrum is therefore un-ambiguously assigned to ·CH(OEt)·CH$_3$ in which coupling occurs with one C$_1$-proton, the three C$_2$-protons, and the two protons on the methylene group. This last splitting (by C$_3$-protons) is similar to that observed in the spectrum from pivalic acid. Di-isopropyl ether behaved analogously to isopropyl alcohol in that the main spectrum was a septet ascribed to the radical formed by abstraction from the α-carbon, each line being an incompletely resolved doublet due to small coupling with the C$_3$-proton, while a weak quartet also present was ascribed to the radical formed by abstraction from the β-carbon. Ethylene glycol dimethyl ether gave a spectrum of which the most intense lines formed a triplet of triplets and can be assigned to ·CH$_2$·O·[CH$_2$]$_2$·O·CH$_3$, C$_3$-protons again being observed. The less intense lines could not be satisfactorily analysed, but may be the spectrum of CH$_3$·O·ĊH·CH$_2$·O·CH$_3$.

Thus, ethers behave similarly to alcohols both in their general reactivity towards the hydroxyl radical and in the fact that, as shown by diethyl ether, abstraction occurs pre-ferentially from the carbon that bears the oxygen substituent.

Ammonia, methylamine, triethylamine, and pyridine had no effect on the ·OH signal,

[11] Norman and Radda, *Proc. Chem. Soc.,* 1962, 138.
[12] Ref. 4, p. 364.

TABLE 2.

Spectra and coupling constants of radicals derived from various aliphatic compounds, and the radicals to which the spectra are assigned.

Compound	Type of spectrum	Coupling constants (G)						Radical
		C_1–H	C_2–H	C_3–H	O–H	N–H	N	
n-Propylamine	Triplet (1 : 2 : 1) of triplets (1 : 2 : 1) [a]	22·5	26·9					·CH$_2$·[CH$_2$]$_2$·NH$_2$
Ethanolamine	Three (1 : 1 : 1) triplets (1 : 2 : 1) of doublets (1 : 1)	18·1	11·8				10·3	·CH(OH)·CH$_2$·NH$_2$
Diethanolamine	Three (1 : 1 : 1) triplets (1 : 2 : 1) of doublets (1 : 1)	18·4	10·8				11·1	·CH(OH)·CH$_2$·NH·CH$_2$·CH$_2$·OH
Hydrazine	9 lines					11·5	11·5	N$_2$H$_4$·$^+$
Acetone	Triplet (1 : 2 : 1), each line an incompletely resolved quartet	20·3		<1				·CH$_2$·CO·CH$_3$
Diethyl ketone	Triplet (1 : 2 : 1) of triplets (1 : 2 : 1) [a]	22·1	24·7					·CH$_2$CH$_2$·CO·C$_2$H$_5$
Formaldehyde	Two (1 : 1) triplets (1 : 2 : 1)	17·8			1·0			·CH$_2$·OH
Acetaldehyde	Two (1 : 1) quartets (1 : 3 : 3 : 1)	16·0	22·2					·CH(OH)·CH$_3$
Chloral hydrate	Septet (1 : 2 : 3 : 4 : 3 : 2 : 1) [b]							·CCl$_2$·CO$_2$H
Diethyl ether	Two (1 : 1) quartets (1 : 3 : 3 : 1) of triplets (1 : 2 : 1)	13·8	21·9	1·4				·CH(CH$_3$)·O·C$_2$H$_5$
Di-isopropyl ether	Two (1 : 1) septets (1 : 6 : 15 : 20 : 15 : 6 : 1) and weak quartet (1 : 3 : 3 : 1)		20·2	<1				·C(CH$_3$)$_2$·O·CH(CH$_3$)$_2$
		21·7	21·7					·CH$_2$·CH(CH$_3$)·O·CH(CH$_3$)$_2$
Ethylene glycol dimethyl ether	Triplet (1 : 2 : 1) of triplets (1 : 2 : 1)	14·6	2·1					·CH$_2$·O·[CH$_2$]$_2$·O·CH$_3$
Dimethyl sulphoxide	Quartet (1 : 3 : 3 : 1)	23·1						·CH$_3$

[a] The assignments of these coupling constants are discussed in the text.   [b] Chlorine coupling, 3·1 G.

even when they were present in concentrations greater than molar. Since these compounds are essentially completely protonated in the acid conditions used, their lack of reactivity is evidently the result of the strong $-I$ effect of the positive pole. n-Propylamine was the simplest aliphatic amine from which abstraction of hydrogen occurred. It gave a spectrum which can reasonably be assigned to $\cdot CH_2 \cdot CH_2 \cdot CH_2 \cdot NH_3^+$, resulting from abstraction from the carbon furthest from the protonated amino-group.

Ethanolamine was much more reactive than unsubstituted amines. Its spectrum, assigned to $\cdot CH(OH) \cdot CH_2 \cdot NH_2$, gave clear evidence of the occurrence of coupling with nitrogen, and there was an indication of further splitting of magnitude about 1 G from the proton on the hydrogen group. Diethanolamine behaved analogously, except that there was no indication of coupling with the hydroxyl proton. Both these compounds evidently owe their reactivity towards $\cdot OH$ to the presence of the hydroxyl substituent.

Hydrazine gave a spectrum of nine equally spaced lines (splitting, 11·5 G) whose relative intensities were close to $1 : 6 : 17 : 30 : 36 : 30 : 17 : 6 : 1$. This is similar to the spectrum of the radical–cation $N_2H_4^+$, obtained by the oxidation of hydrazine with ceric ion, except that the nine lines could not be resolved into the narrowly split groups previously observed.[13] This radical is isoelectronic with the radical–anion $C_2H_4^-$, having an unpaired electron in the antibonding π-orbital, and this may underlie the greater reactivity of hydrazine than of amines, but it is not clear whether the radical is formed by the abstraction of a hydrogen atom from the conjugate acid of hydrazine or by the removal of an electron, by $\cdot OH$, from hydrazine itself.

By analogy with acids, ketones would be expected to be less reactive than alcohols because of the $-I$ effect of carbonyl. This proved to be so, for acetone was required in 0·5 M concentration in order to eliminate the $\cdot OH$ signal completely: the resulting spectrum was a triplet, each of whose lines was an incompletely resolved quartet, and it is ascribed to $\cdot CH_2 \cdot CO \cdot CH_3$. Diethyl ketone gave a complex spectrum from which nine lines forming three triplets could be picked out with reasonable certainty. This spectrum may be assigned tentatively to $\cdot CH_2 \cdot CH_2 \cdot CO \cdot Et$, corresponding to the result for propionic acid.

The three aldehydes investigated behaved in an unexpected manner. Formaldehyde and acetaldehyde, each carefully purified so as to be free of the corresponding alcohols, gave spectra which were identical to those derived from methanol and ethanol, respectively,[1] the spectrum from acetaldehyde containing in addition some weaker lines which could not be analysed. No signals were obtained when the reactions were carried out in the absence of hydrogen peroxide, so that one-electron reduction of the carbonyl groups by titanous ion cannot be responsible for the generation of the radicals. The mechanism of formation of these free-radical reduction products has been discussed separately.[14]

Chloral hydrate gave a spectrum (Fig. 3) with a pattern characteristic of coupling with two chlorine nuclei; there was no indication of coupling with protons. The pattern and coupling constant are identical to those obtained from dichloroacetic acid, and $\cdot CCl_2 \cdot CO_2H$ is the simplest radical which could give rise to the observed spectrum. The formation of this radical requires that chlorine be lost from the organic compound, and, consistently with this, both chloride ion and chlorine were detected in the reaction products. We suggest that this radical results from reaction (4), in which the second step may be regarded as an intramolecular analogue of the intermolecular electron-transfers observed previously.[14]

$$CCl_3 \cdot CH(OH)_2 \xrightarrow{\cdot OH} CCl_3 \cdot \dot{C}(OH)_2 \longrightarrow \dot{C}Cl_2 \cdot CO_2H + HCl \qquad (4)$$
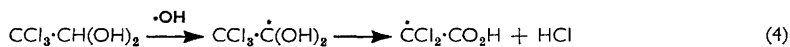
Finally, two other compounds with strongly electron-attracting substituents attached to methyl were examined. Nitromethane had no discernible effect on the $\cdot OH$ signal, but dimethyl sulphoxide, although comparatively unreactive, gave a quartet identical

[13] Adams and Thomas, *J. Chem. Phys.*, 1963, **39**, 1904.
[14] Buley and Norman, *Proc. Chem. Soc.*, 1964, 225.

View Online

[1964] *Electron Spin Resonance Studies of Oxidation. Part II.* 3633

with that of the methyl radical.[1] This radical may arise from addition of ·OH to the sulphoxide group and subsequent cleavage of a C–S bond.

Coupling Constants.—(a) C_1-*Protons.* Inspection of the data in Tables 1 and 2 shows that the substitution of any one of the groups examined for a hydrogen atom in ·CH$_3$ or ·CH$_2$X reduces the coupling constant of the C_1-proton(s). This is indicative of the reduction of the spin density at the carbon which bears the unpaired electron, and the effectiveness with which different substituents produce this result can be summarised as follows:

$$\text{OAlk} > \text{OH} > {>}\text{CO} \sim \text{Cl} > \text{CO}_2\text{H} > \text{Alk} > \text{H}$$

It is notable that both carbonyl and carboxyl groups diminish the ease of abstraction of hydrogen from the adjacent carbon relative to that from a distant C–H group, and yet both are able to delocalise the unpaired electron, as evidenced by the relative values of the coupling constants for ·CH$_3$, ·CH$_2$·CO·Me, and ·CH$_2$·CO$_2$H. These two statements are not, however, inconsistent, and moreover they have a close parallel: chlorine and bromine atoms abstract hydrogen from the methyl group of *p*-nitrotoluene less rapidly than from toluene,[15] although the unpaired electron should be further delocalised in the *p*-nitrobenzyl radical than in the benzyl radical. The factors which influence the stabilisation of one radical relative to another do not necessarily have the same relative influence on the transition states which precede those radicals. In the case of abstraction from C–H both by chlorine and bromine atoms and by the hydroxyl radical, in each of which the unpaired electron is associated with a strongly electronegative atom, electron-attracting groups in the vicinity of the C–H bond can decrease the stability of the transition state, and hence the rate of abstraction,[15] while nevertheless stabilising by delocalisation the radical formed.

(b) C_2-*Protons.* Exceptionally large variations were noted in the magnitude of the coupling with C_2-protons in the radicals (I), (II), and (III), derived from lactic acid, malic acid, and tartaric acid. Coupling with C_2-protons has been attributed to a hyperconjugative mechanism, and its magnitude should be dependent on the dihedral angle, θ, between the C_2–H bond and the *p*-orbital which contains the unpaired electron, being minimal when the C_2–H bond lies in the nodal plane of this *p*-orbital ($\theta = 90°$), maximal when $\theta = 0°$, and in general proportional to $\cos^2 \theta$.[16] In (I) the average value of $\cos^2 \theta$ is 0·5, but in (II) and (III) the other substituents on the C_2-carbon should give rise to certain preferred conformations as a result of rotation about the C_1–C_2 bond. The lower values for the C_2-coupling constants in these instances are, then, consistent with the average values of $\cos^2 \theta$ being less than 0·5.

Detailed examination of the hypothesis that the magnitude of C_2-coupling follows a $\cos^2 \theta$ relationship requires the study of radicals in which the value of θ is known. As an initial approach to this problem we have investigated the reaction of cyclobutane-1,1-dicarboxylic acid with the titanous-peroxide system. This gave a spectrum (Fig. 6)

(VIII)   (IX)

which is apparently due to a mixture of the radicals (VIII) and (IX), the former giving two quintets, each of whose three centre lines overlaps with the lines of the two triplets given by the latter.

[15] Ref. 4, Ch. 8.
[16] Symons, *Tetrahedron*, 1962, **18**, 333.

View Online

3634   *Electron Spin Resonance Studies of Oxidation.   Part II.*

The salient feature of this spectrum in the present context is that, while the extent of coupling with the C_1-proton is of the usual order of magnitude for such structural environments ($21 \cdot 5$ G in each case), the coupling constants for the four C_2-protons in structure (VIII) and the two C_2-protons in structure (IX), **37·0** and **38·5** G, respectively, are considerably larger than those in radicals of similar structure but in which there is essentially free rotation about the C_1–C_2 bond (*e.g.*, $\cdot CH_2 \cdot CH_2 \cdot CO_2H$; see Tables 1 and 2). The cyclobutane ring is slightly buckled from the planar configuration,[17] but it is reasonable to assume for the present purposes that the radicals (VIII) and (IX) have planar carbon rings, particularly since some of the eclipsing interactions which lead to buckling in cyclobutane itself should be absent in the two radicals because the C_1-proton and the C_2-substituents are now in the staggered conformation. Thus, θ is approximately $30°$, giving a ratio for $\cos^2 \theta$ for (VIII) or (IX) to $\cos^2 \theta$ (average) for a freely rotating system of $1 \cdot 5$. This is close to the ratios of the coupling constants for the C_2-protons in (VIII) and (IX) to that of the C_2-proton in $\cdot CH_2 \cdot CH_2 \cdot CO_2H$ ($1 \cdot 39$ and $1 \cdot 45$, respectively).

Assignments of Coupling Constants.—Some of the coupling constants reported in Tables 1 and 2 which could not be unambiguously assigned earlier to specific protons may be assigned on the basis of the above discussion. The larger of the two doublet splittings in the spectra of the radicals formed by addition to maleic (or fumaric) acid and crotonic acid are of the order usually found for C_1-protons and are assigned as such, while the smaller value in each case is evidently due to the C_2-proton, and its magnitude is governed by the conformational situation. Similarly, the smaller of the two values for propionic acid, n-propylamine, and diethyl ketone is assigned to the C_1-protons and the larger to the C_2-protons.

EXPERIMENTAL

The spectrometer, the flow system, and the procedure for carrying out the reactions have been described.[1] The stability and reproducibility were checked periodically by examining the spectrum of an alkaline solution of potassium nitrosodisulphonate in a static system and, more frequently, by examining the spectrum from methanol in the flow system. In this way coupling constants could be measured to within $\pm 0 \cdot 3$ G.

[17] Dunitz and Schomaker, *J. Chem. Phys.*, 1952, **20**, 1703; Almenningen, Bastiansen, and Skancke, *Acta Chem. Scand.*, 1961, **15**, 711; Rothschild and Dailey, *J. Chem. Phys.*, 1962, **36**, 2931.