Electron Spin Resonance Studies. Part 58.[1] The Formation and Reactions of Some Aliphatic Radical-cations in Aqueous Solution

By **Bruce C. Gilbert,* Richard O. C. Norman,** and **Peter S. Williams,** Department of Chemistry, University of York, Heslington, York YO1 5DD

Evidence is presented that reaction of $Cl_2^{-\cdot}$ with vinyl ethers proceeds *via* the formation of the radical-cations of the parent compounds. These species are not directly detectable by e.s.r., but the spectra of radicals formed in one or more of three further reactions have been characterized. These reactions are hydration, addition to the parent molecule, and deprotonation [*e.g.*, $CH_2{=}CHOEt^{+\cdot}$ (from ethyl vinyl ether) yields the hydroxylated radicals $\cdot CH(OEt)CH_2OH$ and $\cdot CH_2CH(OH)OEt$ and the 'dimer' radical $\cdot CH(OEt)CH_2CH_2CH(OH)OEt$]. It has been confirmed that analogous radical-cations are also formed during the reactions of the hydroxyl radical with enol ethers at low pH and by elimination reactions of radicals of the type $\cdot CH(OR)CH_2X$ (with X = Cl, OH, or OMe). It is shown that furan is an effective spin trap for the radical-cations involved in these reactions.

E.S.R. studies of the reactions of $SO_4^{-\cdot}$ with a variety of aromatic compounds have provided evidence that radical-cations are intermediates;[2-5] in some cases (*e.g.* with methoxy-substituted benzoate anions) they are directly detectable.[3] Radical-cations have also been proposed as key intermediates in the oxidation of aromatic compounds with, for example, the hydroxyl radical in acid solution,[6] and, at least for electron-rich substrates such as *p*-methoxyphenol, with $Cl_2^{-\cdot}$.[7] Although radical-cations have often been suggested as participating in the oxidation of aliphatic compounds [*e.g.* in the oxidation of some alkenes with[4] $SO_4^{-\cdot}$ and in the acid-catalysed rearrangement of αβ-dioxygen-substituted and related radicals, such as $\cdot CH(OMe)CH_2OH$[8] and some β-phosphato-substituted analogues[9]], there is little direct evidence for their formation; one exception is the report[10] of the e.s.r. spectrum of $(MeO)_2C{=}CH_2^{+\cdot}$, formed by loss of Cl^- from the radical $(MeO)_2\dot{C}{-}CH_2Cl$.

We set out to confirm the presence of radical-cations in some aliphatic systems and to study their reactions. Three approaches were employed. First, we investigated the reactions of $Cl_2^{-\cdot}$ and $SO_4^{-\cdot}$, both of which are believed to be effective one-electron transfer agents, with some electron-rich substrates, notably enol ethers. Secondly, we attempted to discover effective spin-traps for radical-cations in aqueous solution. Thirdly, we extended previous studies of the acid-catalysed reactions of radicals of the types $\cdot CH(OR)CH_2OR$.

RESULTS AND DISCUSSION

Introduction.—Reactions were carried out in the cavity of an e.s.r. spectrometer, by employing a continuous three-way flow mixing system with a mixing time of *ca.* 80 ms. The hydroxyl radical was generated with the Ti^{III}–H_2O_2 couple and $SO_4^{-\cdot}$ with the Ti^{III}–$S_2O_8^{2-}$ couple, with (for pH >2) addition of the disodium salt of ethylenediaminetetra-acetic acid (edta) as sequestering agent for Ti^{III}; these systems have been described previously.[4,5,8] The radical-anion $Cl_2^{-\cdot}$ was generated in two ways. First, in the pH range 0—2, the reaction of $\cdot OH$ (from Ti^{III}–H_2O_2) with Cl^- (at concentrations of at least 1 mol dm^{-3}) was employed. Under these conditions[7,11] $\cdot OH$ is effectively scavenged by chloride ion [reaction (1)], rather than by organic substrates present at much lower concentrations (*cf.* an estimate[11] for k_1 of 4.3×10^9 dm^3 mol^{-1} s^{-1}, a value close to the diffusion-controlled limit); at low pH values, production of $Cl_2^{-\cdot}$ *via* reactions (2) and (3) then follows (k_{-1} is 6.1×10^9 s^{-1}, k_2 is 2.1×10^{10} dm^3 mol^{-1} s^{-1}, k_3 is 2.1×10^{10} dm^3 mol^{-1} s^{-1}, and k_{-3} is 1.1×10^5 s^{-1}; *cf.* ref. 11). Secondly, in the pH range 3—9, where the overall production of $Cl_2^{-\cdot}$ from $\cdot OH$ and Cl^- becomes less effective, we employed the reaction between $SO_4^{-\cdot}$ (from Ti^{III}–$S_2O_8^{2-}$) and Cl^- (with the latter at concentrations >1 mol dm^{-3}); then, reaction (4) (with k_4[12] 3.1×10^8 dm^3 mol^{-1} s^{-1}), followed by (3), generates $Cl_2^{-\cdot}$. Evidence that $Cl_2^{-\cdot}$, rather than $\cdot OH$ or $SO_4^{-\cdot}$, is the reactive species under the appropriate conditions is described in the sequel.

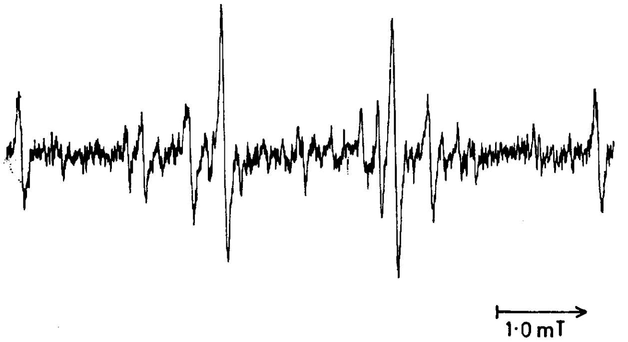


FIGURE 1 E.s.r. spectra of $\cdot CH_2CH(OEt)OH$ (2) and $\cdot CH(OEt)CH_2OH$ (1), formed in the reaction of $\cdot OH$ with ethyl vinyl ether at pH 1.0

$$HO\cdot + Cl^- \rightleftharpoons HOCl^{-\cdot} \qquad (1)$$

$$HOCl^{-\cdot} + H^+ \longrightarrow H_2O + Cl\cdot \qquad (2)$$

$$Cl\cdot + Cl^- \rightleftharpoons Cl_2^{-\cdot} \qquad (3)$$

$$SO_4^{-\cdot} + Cl^- \longrightarrow Cl\cdot + SO_4^{2-} \qquad (4)$$

Oxidation of Alkyl Vinyl Ethers.—(i) *Results.* When ethyl vinyl ether was oxidised with $Cl_2^{-\cdot}$ at pH <2, four different species could be detected, in relative proportions depending on the precise conditions employed. Of these, the two hydroxylated species $\cdot CH(OEt)CH_2OH$ (1) and $\cdot CH_2CH(OH)OEt$ (2) have been previously detected during the oxidation[13] of this substrate with $\cdot OH$ (details of their spectra are given in Table 1; see also Figure 1).

TABLE 1

Radicals detected during the oxidation of alkyl vinyl ethers

Substrate	Radical	Hyperfine splittings (mT) [a] $a(\alpha\text{-H})$	$a(\beta\text{-H})$	$a(\mathrm{OC}H)$	$a(\gamma\text{-H})$	g [b]
$\mathrm{EtOCH{=}CH_2}$	$\mathrm{EtO\dot{C}HCH_2OH}$ (1)	1.72	0.88	0.175		2.0032
	$\mathrm{\cdot CH_2CH(OH)OEt}$ (2)	2.24	1.88			2.0025
	$\mathrm{EtO\dot{C}HCH_2CH_2CH(OH)OEt}$ [c] (3)	1.425	1.96 1.94	0.135 [c]	0.06 [c]	2.0032
	$\mathrm{Me\dot{C}HOCH{=}CH_2}$ (4)	1.45	2.25	0.075		2.0033
$\mathrm{MeOCH{=}CH_2}$	$\mathrm{MeO\dot{C}HCH_2OH}$	1.72	0.88	0.18		2.0031
	$\mathrm{\cdot CH_2CH(OH)OMe}$	2.26	1.92			2.0025
	$\mathrm{MeO\dot{C}HCH_2CH_2CH(OH)OMe}$	1.425	1.975 1.925	0.135 [c]	0.06 [c]	2.0032
	$\mathrm{\cdot CH_2OCH{=}CH_2}$	1.74		0.10		2.0033

[a] ±0.005 except where indicated otherwise. [b] ±0.0001. [c] Analysis verified by spectrum simulation.

The third radical had a spectrum (see Figure 2) which was satisfactorily simulated with the parameters 1.425 (1 H), 0.135 (2 H), and 0.06 mT (2 H), and two slightly different doublet splittings, of 1.96 and 1.94 mT (with g 2.003 2). This is assigned the structure $\mathrm{\cdot CH(OEt)CH_2CH_2CH(OH)OEt}$ (3) on the following basis: first, the g factor is as expected for an oxygen-conjugated species; secondly, the doublet splitting of 1.425 mT, the triplet splitting of 0.135 mT, and the smaller triplet are close to those observed for the α-, ethoxy(methylene)-, and γ-protons in[8] $\mathrm{\cdot CH(OEt)CH_2CH_2CHO}$; and thirdly, and most importantly, the two β-proton splittings (*ca.* 1.9 mT) are slightly different, which is consistent with the presence of a chiral carbon near the radical centre.[14] So small a difference suggests that this centre is not *next* to the β-carbon and is compatible with chirality at the δ-carbon.* The fourth radical, detected in trace quantities, had parameters (see Table 1) closely similar to those of[15] $\mathrm{\cdot CHMeOH}$; the appearance of an additional, small doublet splitting is consistent with this being the spectrum of $\mathrm{\cdot CHMeOCH{=}CH_2}$ (4).

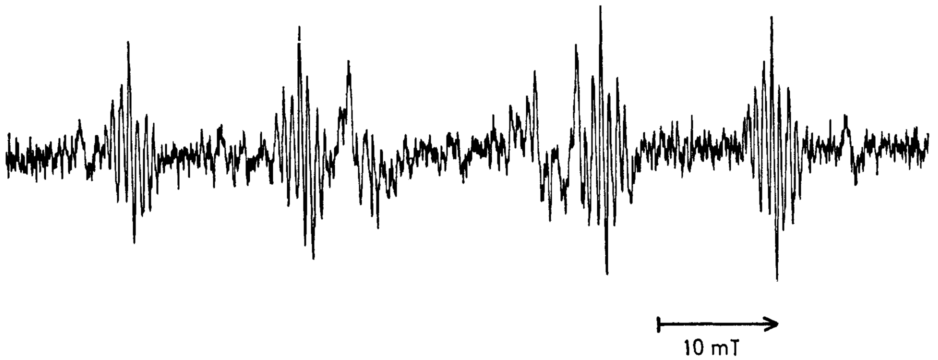


FIGURE 2 E.s.r. spectrum of $\mathrm{\cdot CH(OEt)CH_2CH_2CH(OEt)OH}$ (3), formed in the reaction of $\mathrm{Cl_2^{-\cdot}}$ with ethyl vinyl ether at pH 0.9

Reaction of methyl vinyl ether with $\mathrm{Cl_2^{-\cdot}}$ under similar conditions gave the spectra of $\mathrm{\cdot CH(OMe)CH_2OH}$ and $\mathrm{\cdot CH_2CH(OH)OMe}$, as well as those assigned to $\mathrm{\cdot CH(OMe)CH_2CH_2CH(OH)OMe}$ and $\mathrm{\cdot CH_2OCH{=}CH_2}$ (Table 1).

In experiments with each vinyl ether at low pH it was found that increasing the concentration of the ether led to an increase in the concentration of the 'dimer' radical compared with those of the hydroxylated radicals. The relative concentrations of (1)—(3) (and their counterparts from methyl vinyl ether) also varied considerably with pH in this range and at high pH (when generated using the $\mathrm{SO_4^{-\cdot}}$–$\mathrm{Cl^-}$ system); radical (4) and its counterpart $\mathrm{\cdot CH_2OCH{=}CH_2}$ were only detected (as very weak signals) over a narrow pH range. Table 2 summarizes the results for ethyl vinyl ether for a set of experiments with $[\mathrm{Cl^-}]$ 1 mol dm^{-3}, $[\mathrm{EtOCH{=}CH_2}]$ 0.033 mol dm^{-3}, $[\mathrm{Ti^{III}}]$ 0.003 3 mol dm^{-3}, and $[\mathrm{H_2O_2}]$ 0.022 mol dm^{-3}.† Results for methyl vinyl ether were closely similar.

We can at this stage rule out ·OH and $\mathrm{SO_4^{-\cdot}}$ as the species that react with the vinyl ethers to generate radicals (1)—(4) and the methoxylated analogues since, when maleic acid was substituted for the vinyl ether at pH *ca.* 9 the e.s.r. spectrum of the chlorine adduct[12] $\mathrm{\cdot CH(CO_2^-)\text{–}CHClCO_2^-}$ was detected [$a(\alpha\text{-H})$ 2.02, $a(\beta\text{-H})$ 0.64, $a(^{35}\mathrm{Cl})$ 1.33, $a(^{37}\mathrm{Cl})$ 1.10 mT, and g 2.003 2]; there was only a trace of the $\mathrm{SO_4^{-\cdot}}$-adduct[4] $\mathrm{\cdot CH(CO_2^-)\text{–}CH(OSO_3^-)CO_2^-}$ and no detectable signal from the ·OH adduct.[16] At low pH, the signal detected was likewise assignable to the chlorine-atom adduct $\mathrm{\cdot CH(CO_2H)\text{–}}$

---

* The small value of the splitting from the two γ-protons precludes observation of the expected difference between them; for example, a 10% difference would not be resolved.

† Concentrations quoted are those after mixing.

TABLE 2

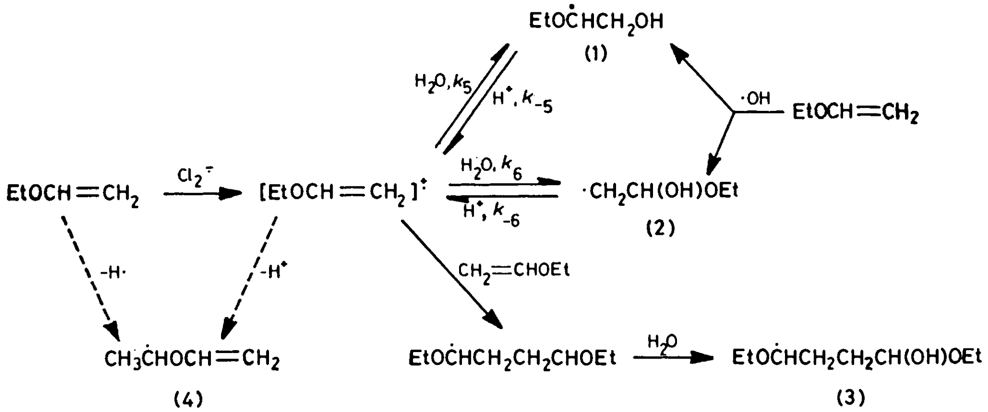
Relative concentrations of radicals (1)—(4) in the oxidation of ethyl vinyl ether under a variety of conditions [a]

Oxidant	pH	[(1)]	[(2)]	[(3)]	[(4)]
$Cl_2^{-\cdot}$	9	5	1	Trace	
	8	5	1	Trace	
	2.0	2	1	Trace	
	1.6	1.25	1	1.25	
	1.2	1	2	4	Trace
	0.5	Trace	0.5	4	Trace
$SO_4^{-\cdot}$	9	6.5	1		
	5	4	1	*b*	
	3.75	2	1	*b*	
$HO\cdot$	4.1	6	1	*c*	
	2.8	3.5	1	*c*	
	1.9	2	1	*c*	
	1.5	1	1.3	*c*	
	1.0	1	3	Trace	Trace
	0.6	Trace	1	2	Trace

[a] For conditions, see text. [b] Radical not detected; overall signal-to-noise ratio poor. [c] Radical not detected; good overall signal-to-noise ratio.

$CHClCO_2H$ [with *g* 2.003 3, *a*(α-H) 2.06, *a*(β-H) 0.71, *a*(^{35}Cl) 1.025, and *a*(^{37}Cl) 0.85 mT].

When ethyl or methyl vinyl ether was oxidized with $SO_4^{-\cdot}$, signals could be detected only in the pH range 3.75—9, and even then the signal-to-noise ratio was generally lower than in the analogous experiment with $Cl_2^{-\cdot}$. However, signals from (1) and (2) (and their methoxylated counterparts) could be discerned, though the ' dimeric ' species noted before could not be detected. Table 2 contains details of the approximate ratios of [(1)] : [(2)].



EtȮCHCH$_2$OH (1); EtOCH=CH$_2$; ·CH$_2$CH(OH)OEt (2); [EtOCH=CH$_2$]$^{+\cdot}$; CH$_3$ĊHOCH=CH$_2$ (4); EtOĊHCH$_2$CH$_2$ĊHOEt; EtOĊHCH$_2$CH$_2$CH(OH)OEt (3)

SCHEME 1

The reaction of $\cdot OH$ with $CH_2{=}CHOEt$ was found to have some features similar to those in the reaction of $Cl_2^{-\cdot}$. Thus, as noted previously,[13] the hydroxylated radicals $\cdot CH(OEt)CH_2OH$ (1) and $\cdot CH_2CH(OH)OEt$ (2) were detected, the former predominating at high pH and the latter at low pH (see Table 2). However, in contrast with the results for $Cl_2^{-\cdot}$, no dimeric radical (3) could be detected above pH 1, even though the overall signal-to-noise ratio was generally good (contrast, for example, Figures 1 and 2). Weak signals from $\cdot CH(OEt)CH_2CH_2CH(OH)OEt$ were, however, just discernible at pH 1, and increased in intensity below this (see Table 1); traces of radical (4) were also detected at very low pH. Methyl vinyl ether behaved in similar fashion.

(ii) *Mechanistic implications.* We have previously argued [13] that the high ratio of [(1)] : [(2)] in the reaction of $\cdot OH$ with $CH_2{=}CHOEt$ at high pH reflects the kinetic control of attack of the electrophilic radical, whereas acid-catalysed interconversion of these at low pH (below *ca.* 1.3) leads to the predominance of the more stable (though non-conjugated [13]) radical (2). The mediation of a radical-cation in the latter process was suggested.

The detection of hydroxylated radicals in the reaction of $Cl_2^{-\cdot}$ at all pH values can be accounted for through the formation of a radical-cation $CH_2{=}CHOR^{+\cdot}$ (either directly, or *via* rapid loss of Cl^- from a chlorine-atom adduct); this would then hydrate to give $\cdot CH_2CH(OH)OR$ and $\cdot CH(OR)CH_2OH$ in proportions which, at high pH, should reflect the ***kinetic*** control of hydration, and, at low pH, should reflect (as in the reaction with $\cdot OH$) the occurrence of acid-catalysed interconversion (see Scheme 1). The radical $\cdot CH(OEt)CH_2CH_2CH(OH)OEt$, which is formed at all pH values from $Cl_2^{-\cdot}$, could in principle be derived from addition of $\cdot CH_2CH(OH)OEt$ to the vinyl ethers; however, this does not appear to be an important route since strong signals from $\cdot CH_2CH(OH)OEt$ during the oxidation of $CH_2{=}CHOEt$ with $\cdot OH$ at pH *ca.* 1.5 were not accompanied by signals of significant intensity from $\cdot CH(OEt)CH_2CH_2CH(OH)OEt$. We envisage instead that the dimer radical results from addition of the radical-cation $CH_2{=}CHOEt^{+\cdot}$ (formed from $Cl_2^{-\cdot}$ at all pH values) to the vinyl ether (see Scheme 1)—a process that is presumably facilitated by the electrophilic nature of the former species and the electron-rich nature of the latter—followed by rapid hydration. It is notable that anodic oxidation of enol ethers leads to the formation of dimeric products in good yield [*e.g.* $EtO(MeO)CHCH_2CH_2CH(OMe)OEt$ from $EtOCH{=}CH_2$ in methanol].[17] Although, as has been pointed out,[17] several reaction mechanisms are possible for this conversion, each involving the radical-cation (*e.g.* its dimerization or its addition to the parent molecule), our results suggest that the second of these is, at least, a feasible reaction and they establish that the orientation of addition (tail-to-tail) is as expected from considerations based on electron delocalization in the product.[17]

The increase in the concentration of (3) at the expense of (1) and (2) in the reaction with $Cl_2^{-\cdot}$ when the pH is reduced (see Table 2) presumably reflects the increased importance of the acid-induced reversal of one or both of the radical-cation hydration reactions, so increasing the steady-state concentration of $[CH_2{=}CHOEt]^{+\cdot}$ and thence of (3). In the reaction with •OH, (3) can arise only at low pH, since formation of the precursor radical-cation now requires acid-catalysed elimination of hydroxide from the adducts (1) and (2). Although it is possible that radical (4) arises *via* direct hydrogen-abstraction from the vinyl ether by •OH or $Cl_2^{-\cdot}$, an alternative pathway for its formation involves proton-loss from the intermediate radical-cation; evidence for reactions of this type is presented later.

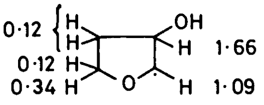
The conversion of $\cdot CH(OEt)CH_2OH$ into the isomer $\cdot CH_2CH(OH)OEt$ has several mechanistic analogues which have been established for radicals derived *via* hydrogen-abstraction from suitable substrates.[8] These include the reactions of $\cdot CH(OMe)CH_2Cl$ and $\cdot CH(OMe)CH_2OAc$, each of which yields mixtures of $\cdot CH(OMe)CH_2OH$ and $\cdot CH_2CH(OMe)OH$ (the former at all pH values, evidently *via* rapid loss of Cl^- and hydration of the resulting cation; the latter *via* an essentially similar route, but only at low pH, when acid assists departure of the leaving group), as well as the more complex examples of $\cdot CH(OH)CH_2OH$ and related compounds (the trapping of radical-cations in some of these examples is described later). We note that in all cases the radicals possess a $+M$ α-substituent and a good leaving group (as well as [13] a conformation in which the bond to the β-substituent eclipses the orbital of the unpaired electron at the radical centre).

Attempts to measure absolute rate constants for certain β-elimination processes will be described subsequently but we can reach a qualitative conclusion concerning the relative ease of loss of OH^- from (1) and (2). Thus the observation that $[(1)] > [(2)]$ at higher pH in the oxidation with $Cl_2^{-\cdot}$ indicates that $k_5 > k_6$ [on the assumption of similar rate constants for termination of (1) and (2)]. If, as seems likely, the dominance of (2) over (1) at low pH [over a whole range of conditions, especially at low concentrations of vinyl ether when reaction to give (3) can be disregarded] implies an *approach* to an equilibrium ratio of $[(2)] : [(1)]$ *via* the radical-cation, then it follows that $k_{-5} \gg k_{-6}$. This is consistent with our expectation based on the structures of the two radicals and also with the related observation that $\cdot CH(OMe)CH_2OMe$ (from 1,2-dimethoxyethane and •OH) reacts to give $\cdot CH(OMe)CH_2OH$ and $\cdot CH_2CH(OH)OMe$ below pH *ca.* 2 (see later), whereas $\cdot CH_2CH(OEt)_2$ [from $BrCH_2CH(OEt)_2$ with [18] $HPO_2^{-\cdot}$; this has *a*(α-H) 2.25 (2 H) α(β-H) 2.00 (1 H) mT, *g* 2.002 5] remains unchanged down to pH *ca.* 1.

Oxidation of 2,3-*Dihydrofuran and* 3,4-*Dihydro*-2H-*pyran*.—(i) *Radical assignments and structural implications*. Oxidation of 2,3-dihydrofuran with •OH at pH *ca.* 8 led to the detection of a complex mixture of radicals. The major species was characterized as the hydroxy-adduct (5) (see Table 3), with splittings from α-, β-, γ-, and γ′-protons assigned as indicated. In particular, the small α-proton splitting is typical of radicals in which the tervalent carbon atom is in a five-membered ring and adjacent to an oxygen atom (see, *e.g.* refs. 19 and 20). The non-equivalence of the methyleneoxy-proton splittings (0.12, 0.34 mT) [in contrast to the equivalence of the splittings (0.18 mT) in tetrahydrofuran-2-yl itself [20]] indicates that a specific ring conformation is preferred, so that the two corresponding C–H bonds subtend markedly different dihedral angles with the *p*-orbital on

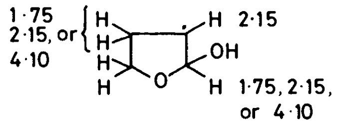
TABLE 3

E.s.r. parameters of radicals detected from 2,3-dihydrofuran and 3,4-dihydro-2*H*-pyran [a, b]



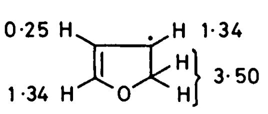
g 2·0031

(5)



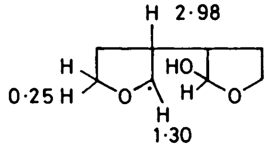
g 2·0025

(6)[c]



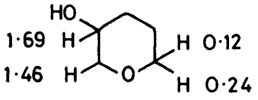
g 2·0034

(7)



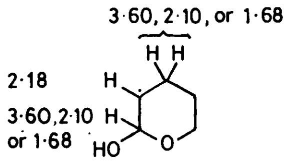
g 2·0030

(8)



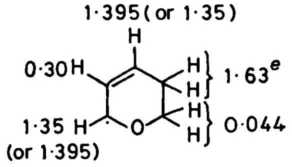
g 2·0031

(9)[d]



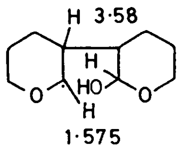
g 2·0025

(10)[c, d]



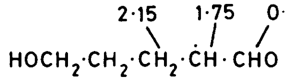
g 2·0031

(11)



g 2·0030

(12)



$HOCH_2{\cdot}CH_2{\cdot}CH_2{\cdot}\dot{C}H{\cdot}CHO$

g 2·0044

(13)

[a] Splittings in mT, ±0.005. [b] *g* ±0.0001. [c] Individual β-proton assignments not possible, see text. [d] Further small splittings, see text. [e] Average splitting, see text.

oxygen which is associated with unpaired electron density (such conformational ' fixing '—with inequivalent splittings from the methyleneoxy-protons but not from the γ-protons—is discussed for radicals of this type in ref. 20). The small value of the single β-proton splitting in comparison with that (2.82 mT) in the unsubstituted radical suggests that the corresponding C–H bond subtends a relatively large dihedral angle with the orbital of the unpaired electron (the interaction is expected to depend on $B\cos^2\theta$); this is consistent with the proton occupying a pseudo-equatorial position in an envelope-type structure [20] in which the bond to the β-hydroxy-group eclipses the orbital of the unpaired electron. The assignment of invididual β-proton splittings in the non-conjugated minor species (6) cannot be made unambiguously, though it may be noted on the basis of the significant differences in these values that the presence of the hydroxy-group again causes a specific ring conformation to be preferred.

A further weak signal, attributed to (7), was also detected at pH *ca.* 8. This signal was much more clearly seen in experiments at low pH when it was accompanied by that from (6) and also by a signal assigned to the dimeric species (8). Radical (7) is assigned the allyl-type structure on the basis of the characteristic [21] splittings of 1.34 and 0.25 mT, its *g* factor, and our finding that it is also derived by hydrogen abstraction from 2,5-dihydrofuran with •OH. The methylene protons in (7) show a remarkably large interaction with the unpaired electron (3.5 mT) (and the expected second-order effect). If the splitting originates simply from interaction with the spin density (*ca.* 50%) on the neighbouring allylic position (with no spin density on oxygen), the expected splitting can be derived simply from the relationship $a_{\mathrm{H}} = \rho B\cos^2\theta$ [with ρ *ca.* 0.5, B *ca.* 5.4 mT (*cf.* ref. 22) and θ *ca.* 30° for a planar ring]; the resulting value is calculated as *ca.* 2.0 mT. On the other hand, if the protons concerned interact with spin density on the allylic carbon *and* on oxygen, then, as Whiffen has pointed out,[23] the appropriate relationship for hyperconjugative interaction is $a_{\mathrm{H}} = (c_{\mathrm{C}} + c_{\mathrm{O}})^2 B\cos^2\theta$, where c_{C} and c_{O} are the coefficients of the molecular orbital containing the unpaired electron on, respectively, the carbon and oxygen atoms adjacent to the methylene protons. If we use B 5.4 mT, θ 30°, c_{C}^2 0.58 (derived from the observed α-proton splitting of 1.34 mT together with the McConnell [24] relationship for α-proton splittings, with Q −2.3), then the observed value of 3.5 mT for the methylene protons implies a value for the $p(\pi)$ spin density on oxygen (c_{O}^2) of 0.042. This is in the range expected from a detailed analysis of the e.s.r. spectra of a variety of oxygen-conjugated radicals and also from the results of INDO and Hückel MO calculations,[25] and suggests that the assignment of the spectrum from (7), with its attendant stereochemical and electronic implications, is correct.

Our assignment of the spectrum to the adduct radical (8) is made on the basis of the *g* factor, α-proton splitting (typical of an oxygen-conjugated radical), the large (pseudo-axial) β-proton interaction, and long-range coupling across oxygen (0.25 mT) (further small splittings were incompletely resolved), as well as by analogy with the assignments of spectra to the ' dimer ' radicals in the corresponding reaction of acyclic vinyl ethers with $\mathrm{Cl_2}^{-\cdot}$ and •OH at low pH.

Reaction of 2,3-dihydrofuran with $\mathrm{Cl_2}^{-\cdot}$ at pH *ca.* 1.0 led to the detection of radicals (7) and (8); at high pH the signals were weak and could not be characterized. Data on the relative proportions of radicals (5)—(8) formed in the reactions of •OH and of $\mathrm{Cl_2}^{-\cdot}$ as a function of pH are collected together in Table 4.

TABLE 4

Relative proportions of radicals derived from cyclic enol ethers

A

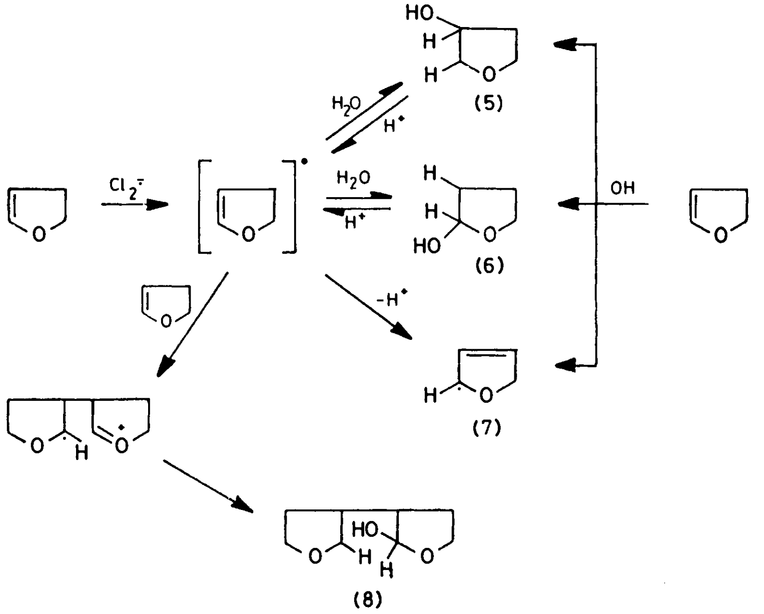
From 2,3-dihydrofuran		[(5)]	[(6)]	[(7)]	[(8)]
Oxidant	pH				
HO•	8.5	vs	m	w	
	6.3	vs	m	w	
	3.2	m	m	w	
	2.4		m	s	m/s
	1.7		m	s	s
	0.7			s	vs
$\mathrm{Cl_2}^{-\cdot}$	0.9			w	vs
	0.6			w	vs

B

From 3,4-dihydro-2*H*-pyran		[(9)]	[(10)]	[(11)]	[(12)]	[(13)]
HO•	9.0	s	w	w		
	5.5	s	w	w		
	3.7	w	m	w		
	3.0		m	m		
	2.0		m	s		w
	1.25		m	s	m	m
$\mathrm{Cl_2}^{-\cdot}$	1.0		w	s	m	m
	0.5			s	m	m

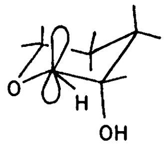
Tables 3 and 4 also contain details of the parameters and relative concentrations of radicals derived from 3,4-dihydro-2*H*-pyran and assigned the structures (9)—(13). Of these, the radicals (9)—(12) are analogous to radicals (5)—(8) derived from 2,3-dihydrofuran, but some structural features are worthy of special note. First, there is evidence in the spectrum of the hydroxy-adduct (9) for a considerable extent of conformational fixing [with the β-hydroxy-group approximately axial, *cf.* (5)]; further interaction with γ- or δ-protons (*ca.* 0.04 mT) was also discerned, but analysis and assignment are ambiguous. Secondly, for the non-conjugated radical (10) the detection of non-equivalent β-proton splittings also indicates that a preferred conformation is adopted (with the hydroxy-group presumably occupying an equatorial position); further small splittings in the spectrum of this radical [a(2H) 0.05, a(1H) 0.10 mT] cannot be unambiguously assigned. Thirdly, in the allylic radical (11) the β-proton pattern comprises a doublet, a 3.26 mT; comparison with other radicals with six-membered rings [19] suggests that this is the sum of the two β-proton splittings in a radical undergoing chair–chair flipping at a rate in the intermediate region (to give a 1 : broad : 1 pattern with the central line undetectable). The average splitting of 1.63 mT is considerably less than that for the analogous species (7) because the methylene protons in (11) are not adjacent to a second site bearing spin density. Fourthly, the radical (12) is assigned its structure on the basis of its parameters and by analogy with the behaviour of the other vinyl ethers. Finally, as the pH was lowered and signals from (11) and (12) appeared, a fifth signal, with g 2.004 4, a(1H) 1.75, a(2H) 2.15, and a(1H) 0.18 mT, was also clearly detected. These parameters are as expected for a radical containing the partial structure $-CH_2-\dot{C}H-CH=O$ (*cf.* the closely similar splittings for the α-, β-, and formyl protons in[8] •CHMeCHO and the characteristic g value). Although there is no further information on the remainder of the alkyl chain in this radical, mechanistic considerations (see later) indicate that the radical probably has the structure •CH(CHO)-$CH_2CH_2CH_2OH$ (13).

(ii) *Mechanistic implications*. The reactions of 3,4-dihydro-2*H*-pyran clearly parallel those of 2,3-dihydrofuran and these substrates show trends in common with those exhibited by the acyclic vinyl ethers. Thus the changes observed during the reactions with •OH, from spectra dominated by hydroxylated species [(5), (6), (9), and (10)] at high pH to those dominated by allylic radicals and dimers [(7), (8), (11), and (12)] at low pH are similarly interpreted in terms of the acid-catalysed decomposition of first-formed hydroxy-adducts into radical-cations, followed by subsequent deprotonation (to give allylic radicals) or addition to more vinyl ether. The detection of signals from (7) and (11) in the reactions of •OH at high pH indicates that some direct allylic hydrogen abstraction occurs in competition with the addition reaction. The increase in intensity of these signals at low pH coupled with their detection in the reactions of $Cl_2^{-\bullet}$ (which would not be expected to be effective in hydrogen-abstraction reactions) suggests that an important route to their formation involves deprotonation of the appropriate radical-cation. Scheme 2 illustrates the reactions involved (for 2,3-dihydrofuran).

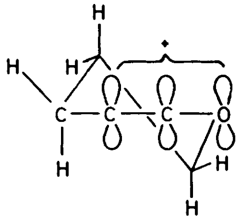


SCHEME 2

Several points of detail concerning the behaviour of 2,3-dihydrofuran and 3,4-dihydro-2*H*-pyran should be noted. First, for the former, the disappearance of (5), then (6), as the pH is lowered is interpreted in terms of the readier loss of hydroxyl from the former compared with the latter, *i.e.* with a higher rate constant for the αβ-dioxygen-conjugated species, as with the analogous acyclic species. Secondly, the loss of hydroxyl from the pyran-derived radical (9) evidently occurs more readily than from the furan analogue (5), as judged by the observation that, in the reaction with •OH, the former has almost disappeared by pH 3.7 as the solution is acidified, whereas for the latter the corresponding pH is <3.2 (see Table 4). This may well reflect the greater ease with which the former radical (with its six-membered ring) can achieve a conformation with the β-hydroxy-group eclipsing the orbital of the unpaired electron [and in an axial position, *cf.* (14)]. Thirdly, it is interesting that the ratio [allyl] : [dimer] is much larger for the pyran than the furan; again, it seems likely that deprotonation, relative to addition, is faster for the six-



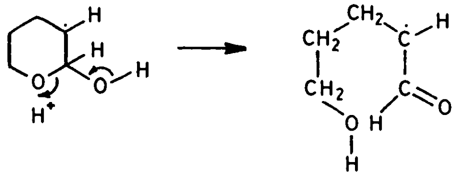
(14)



(15)

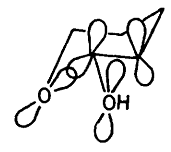
membered ring radical-cation, in which an axial proton is ideally placed for elimination [*cf.* (15)].

Finally, we note that a lowering of pH for reaction of 3,4-dihydro-2*H*-pyran led to the detection of a signal from a carbonyl-conjugated radical as the signal from the non-conjugated radical (10) disappeared (in contrast, no corresponding radicals could be detected from 2,3-dihydrofuran or the acyclic analogues). We believe that the carbonyl-conjugated radical has structure (13) and that it derives from acid-catalysed ring-opening of (10) [reaction (5)]. If this assignment and mechanistic analysis are correct, then it seems likely that the occurrence of ring opening for the six-membered cyclic radical (10) but not the five-membered analogue (6) follows from the fact that at the transition state for the former, the C(*p*)-orbital of the incipient carbonyl group is better placed for overlap with the orbital of the unpaired electron [*cf.* structure (16)].



(5)

(10) (13)



(16)

Spin-trapping of Radical-cations.—Our mechanistic interpretation of the formation of ' dimeric ' species in the oxidation of vinyl ethers with $Cl_2^{-\cdot}$, $SO_4^{-\cdot}$, and, at low pH, ·OH is based on the addition of an (electrophilic) radical-cation to a further molecule of the electron-rich substrate. If this is correct, then it represents an example of spin-trapping of a species which is not itself directly detectable. In an attempt to extend the corroborative usefulness of such a procedure we have, first, extended our studies to the use of furan as a potential trap in the systems described above and, secondly, carried out other reactions thought to involve radical-cations in the presence of a variety of enol ethers, including ethyl vinyl ether and furan.

(i) *The use of furan as a spin trap*. Reaction of ·OH with furan in aqueous solution at pH *ca.* 1 gave a strong signal of the adduct (17) (see Table 5), with parameters closely similar to those assigned [26] to the same radical formed during photolysis. At high pH (>*ca.* 7.5), the ring-opened radical (18) was the only species detected; the mechanism for its formation *via* (17) has previously been discussed.[26] Both (17) and (18) were detected in the pH range 6.5—7.5. Reaction of furan with $Cl_2^{-\cdot}$ at pH < *ca.* 2.0 led solely to the detection of (17), formed presumably by hydration of a first-formed radical-cation.

When the oxidation of furan (0.033 mol dm^{-3}) with $Cl_2^{-\cdot}$ was carried out at pH 1.4 in the presence of ethyl vinyl ether (0.07 mol dm^{-3}), the e.s.r. spectrum comprised a mixture of signals; these were from $\cdot CH_2CH(OH)OEt$ (2) and (17), as well as one with *a*(1H) 3.27, *a*(2H) 1.34, *a*(1H) 0.215, *a*(2H) 0.09 mT, and *g* 2.003 1 (see Figure 3). This is assigned to the radical (19), a ' crossed dimer ', formally resulting from the addition of $\cdot CH_2CH(OH)OEt$ to furan, on the basis of the *g* value, two allyl-type splittings (1.34 mT), and the small triplet attributed to the γ-CH_2 protons. Reaction of $Cl_2^{-\cdot}$ with furan and methyl vinyl ether gave rise to closely similar signals (the ' crossed-dimer ' radical had exactly the same splittings and *g* value as its analogue). The ' crossed-dimer ' radicals were also detected, though at lower concentrations, in oxidations with ·OH at low pH (<*ca.* 1). Our mechanistic interpretation (see Scheme 3) is that radical (19) is formed by the addition of a first-formed radical-cation from the vinyl ether to furan rather than to a further molecule of vinyl ether, possibly on account of the extra stability in the allyl species so obtained. (Evidence that the radical is generated in this way rather than by attack of furan radical-cation on the vinyl ether is presented later.) The fact that the adduct formed has the unpaired electron in the furan ring and the charge adjacent to the alkoxy-group, rather than *vice versa*, is consistent with this reaction being effectively a radical addition to furan, the structure of the (electrophilic) radical-cation being best represented as $\cdot CH_2-\overset{+}{C}HOEt$ [*cf.* the structure $\cdot CH_2-\overset{+}{C}(OMe)_2$ proposed for the 1,1-dimethoxyethylene radical-cation [10]].

It is perhaps surprising that at no stage was a spectrum detected which could be assigned to an adduct of the furan radical-cation with a further molecule of furan; this may reflect a comparative lack of reactivity of the more delocalized radical-cation.

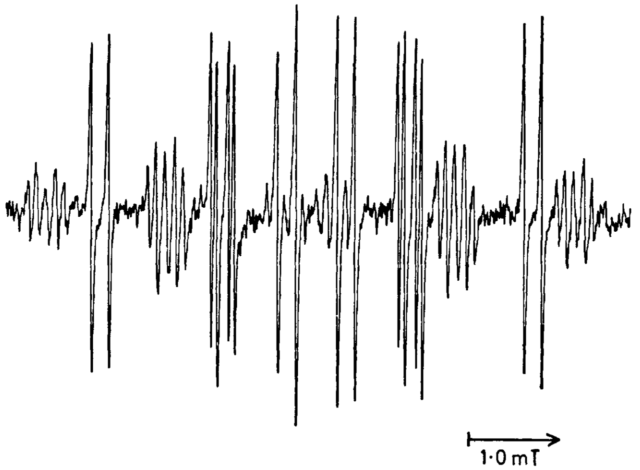
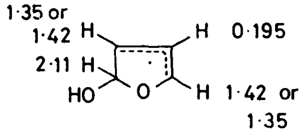
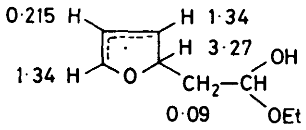
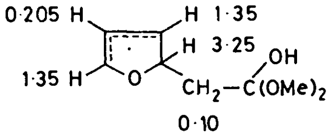
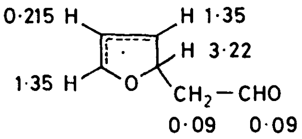
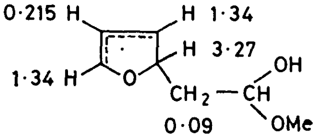


FIGURE 3 E.s.r. spectrum of radical-adducts (17) and (19) formed during oxidation of ethyl vinyl ether with $Cl_2^{-\cdot}$ in the presence of furan

(ii) *Radical-cations from hydrogen-abstraction reactions*. The results described so far have demonstrated that radical-cations formed in reactions of electron-rich alkenes with $Cl_2^{-\cdot}$ and with hydroxyl at low pH can be characterized *via* their adducts with effective spin-traps. We also extended this study in an attempt to trap radical-cations formed by elimination reactions of radicals formed from saturated substrates by way of hydrogen-abstraction.

TABLE 5

E.s.r. spectra of radical-adducts of furan [a]

Substrate	Oxidant	pH	Radical	g [b]
Furan	$\{\cdot OH$ $Cl_2^{-\cdot}$	1	 (17)	2.0027
	·OH	9	$[O{=}CH{-}CH{=}CH{-}CHO]^{-}$ a_H 0·58, 0·485, 0·465, 0·45 (18)	2.0042
Furan + CH_2=CHOEt	$Cl_2^{-\cdot}$	1	 (19)	2.0031
Furan + $(MeO)_2CHCH_2Cl$	·OH	0—9	 (21)	2.0031
Furan + $HOCH_2CH_2OH$	·OH	<2.5	 (22)	2.0031
Furan + $HOCH_2CH_2Cl$	·OH	1—9		
Furan + $MeOCH_2CH_2OMe$	·OH	1	 (23)	2.0031

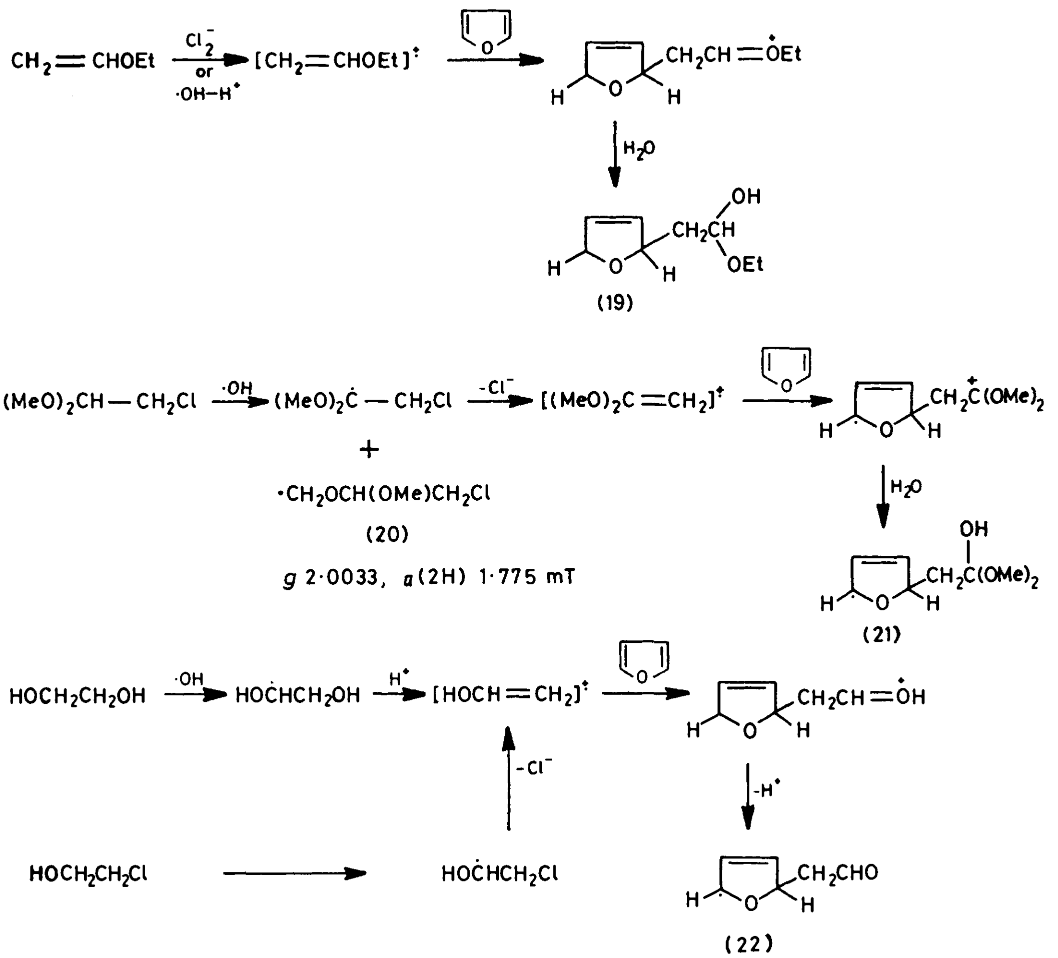
[a] Splittings in mT, ±0.01. [b] ±0.0001.

When 2-chloro-1,1-dimethoxyethane, $(MeO)_2CHCH_2Cl$, was oxidised with ·OH over a wide pH range (0—9), the only signal detected was that attributed to radical (20). Now it would be expected that attack of ·OH on this substrate would yield $\cdot C(OMe)_2CH_2Cl$ preferentially, and that this would readily lose Cl^- to give $(MeO)_2C{=}CH_2^{+\cdot}$ (detected [10] directly during the photolytic generation of ·OH in the presence of this substrate). However, it is possible that such a radical-cation is formed in our system but that its steady-state concentration is too low for detection owing to its ready reduction by Ti^{III} (*cf.* the failure to detect aromatic radical-cations in the presence of this ion [5]). We therefore oxidized this substrate in the presence of furan. In the pH range 0—6, in addition to signals from the furan–OH adduct (17) and radical (20) from the substrate, a spectrum was detected (see Table 5) which is attributed to the structure (21) [we have ruled out as an alternative an adduct with $\cdot CH_2OCH(OMe)CH_2Cl$ in view of our failure to add oxygen-conjugated radicals to vinyl ethers including furan; the e.s.r. signals from $\cdot CH_2OH$ and ·CHMeOH (from reaction of ·OH with methanol and ethanol, respectively) were not removed in the presence of furan or ethyl vinyl ether, nor were adducts detectable]. At pH 8, the radicals detected were (20), (21), and the ring-opened radical (18). We interpret the formation of (21) as involving attack of $(MeO)_2C{=}CH_2^{+\cdot}$ on furan, in a manner analogous to those described previously. Our detection of (18) at pH >7.5 indicates that (21) does not arise by an alternative mode of attack of the furan radical-cation on $(MeO)_2C{=}CH_2$ [which could be formed *in situ* by Ti^{III} reduction of $(MeO)_2C{=}CH_2^{+\cdot}$], for under these conditions the furan–OH adduct undergoes ring-opening rather than elimination of OH^-.

Reaction of $\cdot OH$ with $(MeO)_2CHCH_2Cl$ in the presence of ethyl vinyl ether led to the detection of a radical with *g* 2.003 2, *a*(1H) 1.40, *a*(2H) 1.94, *a*(2H) 0.14, and *a*(2H) 0.055 mT. This is assigned the structure $\cdot CH(OEt)CH_2CH_2C(OMe)_2OH$ by analogy with the data for the 'dimer' radical (**3**) and related species; however, it should be noted that, unlike (**3**), the two β-protons now give equivalent splittings, since the δ-carbon is achiral.* Reaction (6) has evidently occurred.

$$[(MeO)_2C{=}CH_2]^{+\cdot} + CH_2{=}CHOEt \longrightarrow \cdot CH(OEt)CH_2CH_2\overset{+}{C}(OMe)_2 \xrightarrow{H_2O} \cdot CH(OEt)CH_2CH_2C(OMe)_2OH \qquad (6)$$

We also employed furan to intercept a radical-cation formed by the rapid elimination of chloride ion from $\cdot CH(OH)CH_2Cl$ and by the acid-catalysed removal of hydroxide from $\cdot CH(OH)CH_2OH$. Thus, reaction of 2-chloroethanol with $\cdot OH$ in the presence of furan at pH 2 or 4 led to the detection of the furan-derived species (**17**) and (**18**) and an adduct assigned structure (**22**) [with, characteristically, long-range splitting from three equivalent protons (*cf.*[8] $\cdot CH(OH)CH_2CH_2CHO$)], whereas in the absence of furan the species detected are $\cdot CH_2CHO$ and $\cdot CH(OH)CH_2CH_2CHO$ at pH 2, and $\cdot CH_2CH(OH)_2$ and a weak signal from $\cdot CH(OH)CH_2OH$ at pH *ca.* 4, together with traces of $\cdot CHClCH_2OH$ (which would not have been detected in the presence of furan owing to the high signal intensities from the other radicals). We believe that the precursor of the rearranged radicals is $CH_2{=}CHOH^{+\cdot}$, formed by loss of chloride ion from $\cdot CH(OH)CH_2Cl$, and that this is readily trapped by furan (Scheme **3**).



Scheme 3

Oxidation of ethylene glycol at pH 3 in the presence of furan led to the detection of $\cdot CH(OH)CH_2OH$ and the furan–hydroxyl adduct (**17**). However, as the pH was lowered to 2, the spectrum of the former disappeared and was replaced by that of (**22**), *i.e.* the adduct formed *via* reaction of $CH_2{=}CHOH^{+\cdot}$ with furan (see Scheme **3**). No signals from $\cdot CH_2CHO$ and $\cdot CH(OH)CH_2CH_2CHO$ (both of which are detected at low pH in the absence of furan) were observed, and we conclude that the radical-cation intermediate has again been scavenged.

Finally, we studied the behaviour of the radical $\cdot CH(OMe)CH_2OMe$, from 1,2-dimethoxyethane with $\cdot OH$

---

* The alternative structure $\cdot CH(OEt)CH_2CH_2C(O)OMe$, formed by rapid loss of methanol, cannot be ruled out.

at low pH. The spectrum from this radical, which has g 2.003 2, a(α-H) 1.78, a(β-H) 0.88, and a(γ-H) 0.18 mT, gradually diminished in intensity as the pH was lowered below 2, and signals from ·CH(OMe)CH$_2$OH and ·CH$_2$-CH(OH)OMe, in gradually increasing intensity, appeared [*n.b.* despite the close similarity between their splittings, ·CH(OMe)CH$_2$OMe and ·CH(OH)CH$_2$OMe could be clearly distinguished]. This behaviour is best understood in terms of the acid-catalysed loss of the β-methoxy-group in ·CH(OMe)CH$_2$OMe, to give MeOCH=CH$_2^{+\cdot}$, and the subsequent hydration of this radical-cation. In accord with our expectation if a radical-cation is indeed involved, the addition of furan below pH 1.0 led to the detection of the appropriate adduct (**23**) (see Table 5), with splittings identical to those observed for the adduct detected from methyl vinyl ether and $Cl_2^{-\cdot}$ in the presence of furan.

EXPERIMENTAL

E.s.r. experiments were carried out with a Varian E-104 spectrometer equipped with 100 kHz modulation and an X-band klystron. Hyperfine splittings were measured directly from the spectrometer field-scan, this having been calibrated with reference to Fremy's salt (a_N 1.309 1 mT [27]); g factors were measured by comparison with the signal from ·CHMeOH (generated from the reaction of ·OH with ethanol), which has g 2.003 3 (itself measured relative to the g factor for Fremy's salt, 2.005 5 [28]). Simulations of selected spectra were carried out on a DEC-KL10 computer at the University of York with a program which incorporates Lorentzian line-shape and second-order effects. Relative concentrations of radicals were determined from measurements of peak heights (where the appropriate line-widths were the same) or by numerical double integration.[22] pH Measurements (to within ±0.05 units) were made continuously with a Pye PW9410 digital pH meter, coupled to a Russell pH Ltd. electrode inserted into the effluent stream.

An aqueous sample cell with a three-way mixing chamber (with a mixing time 80 ms) was employed in all the experiments; the flow was maintained with a Watson–Marlowe peristaltic pump. Typical conditions were as follows. For reactions of ·OH at pH <2.5, stream (i) contained 0.01 mol dm^{-3} titanium(III) [added as 12.5% (w/v) titanium(III) chloride solution (Fisons technical grade) or 15% (w/v) titanium(III) sulphate (Fisons technical grade], stream (ii) contained *ca.* 0.06 mol dm^{-3} hydrogen peroxide [added as 100 volume hydrogen peroxide (B.D.H. Ltd.)] and in some cases a substrate (where more than one substrate was employed), and stream (iii) contained the substrate at the required concentration. Concentrated sulphuric acid was added usually only to the first stream to bring the final pH (on mixing) to the required value. For experiments with ·OH at pH >2.5, edta (6 g dm^{-3}) was added to stream (i) and the pH was adjusted as required with either concentrated sulphuric acid or ammonia (d 0.880). For experiments with $SO_4^{-\cdot}$, stream (ii) contained instead 0.05 mol dm^{-3} potassium persulphate, and for experiments with $Cl_2^{-\cdot}$ sodium chloride was added, usually to stream (i) alone, to give a concentration after mixing of at least 1 mol dm^{-3}. For experiments with single substrates, the concentration in the third stream was normally 0.1 mol dm^{-3}. For experiments where a second substrate was added as a spin trap, it was generally included in stream (ii) at a concentration of 0.05—0.1 mol dm^{-3}, with the other substrate at a concentration of 0.1—0.2 mol dm^{-3} in the third stream. All solutions were made up in water which had been deoxygenated with a nitrogen purge, and nitrogen was bubbled through the solution prior to mixing.

All materials were commercial samples which were used without further purification.

We thank B.P. Co. Ltd. for the award of a Studentship (to P. S. W.) and Dr. A. J. Burn for helpful discussions.

[9/1149 *Received*, 20*th July*, 1979]

REFERENCES

[1] Part 57, C. Chatgilialoglu, B. C. Gilbert, C. M. Kirk, and R. O. C. Norman, *J.C.S. Perkin II*, 1979, 1084.

[2] P. Neta, V. Madhavan, H. Zemel, and R. W. Fessenden, *J. Amer. Chem. Soc.*, 1977, **99**, 163.

[3] S. Steenken, P. O'Neill, and D. Schulte-Frohlinde, *J. Phys. Chem.*, 1977, **81**, 26.

[4] R. O. C. Norman, P. M. Storey, and P. R. West, *J. Chem. Soc.* (*B*), 1970, 1087.

[5] B. Ashworth, B. C. Gilbert, R. G. G. Holmes, and R. O. C. Norman, *J.C.S. Perkin II*, 1978, 951.

[6] C. Walling and R. A. Johnson, *J. Amer. Chem. Soc.*, 1975, **97**, 363.

[7] K. Hasegawa and P. Neta, *J. Phys. Chem.*, 1978, **82**, 854.

[8] B. C. Gilbert, J. P. Larkin, and R. O. C. Norman, *J.C.S. Perkin II*, 1972, 794.

[9] G. Behrens, G. Koltzenburg, A. Ritter, and D. Schulte-Frohlinde, *Internat. J. Radiat. Biol.*, 1978, **33**, 163.

[10] G. Behrens, E. Bothe, J. Eibenberger, G. Koltzenburg, and D. Schulte-Frohlinde, *Angew. Chem. Internat. Edn.*, 1978, **17**, 604.

[11] G. G. Jayson, B. J. Parsons, and A. J. Swallow, *J.C.S. Faraday I*, 1973, 1597.

[12] O. P. Chawla and R. W. Fessenden, *J. Phys. Chem.*, 1975, **79**, 2693.

[13] D. J. Edge, B. C. Gilbert, R. O. C. Norman, and P. R. West, *J. Chem. Soc.* (*B*), 1971, 189.

[14] See *e.g.* B. C. Gilbert and M. Trenwith, *J.C.S. Perkin II*, 1973, 1834; B. C. Gilbert, J. P. Larkin, and R. O. C. Norman, *ibid.*, 1972, 1272.

[15] W. T. Dixon and R. O. C. Norman, *J. Chem. Soc.*, 1963, 3119.

[16] W. T. Dixon, J. Foxall, and G. H. Williams, *J.C.S. Faraday II*, 1974, 1614.

[17] D. Koch, H. Schäfer, and E. Steckhan, *Chem. Ber.*, 1974, **107**, 3640.

[18] A. L. J. Beckwith, *Austral. J. Chem.*, 1972, **25**, 1887.

[19] A. J. Dobbs, B. C. Gilbert, and R. O. C. Norman, *J. Chem. Soc.* (*A*), 1971, 124.

[20] C. Gaze and B. C. Gilbert, *J.C.S. Perkin II*, 1978, 503.

[21] See *e.g.* J. K. Kochi, *Adv. Free Radical Chem.*, 1975, **5**, 224.

[22] See *e.g.* P. B. Ayscough, 'Electron Spin Resonance in Chemistry', Methuen, London, 1967.

[23] D. H. Whiffen, *Mol. Phys.*, 1963, **6**, 223.

[24] H. M. McConnell, *J. Chem. Phys.*, 1956, **24**, 764; H. M. McConnell and D. B. Chesnut, *ibid.*, 1958, **28**, 107.

[25] C. Gaze and B. C. Gilbert, *J.C.S. Perkin II*, 1979, 763.

[26] R. H. Schuler, G. P. Laroff, and R. W. Fessenden, *J. Phys. Chem.*, 1973, **77**, 456.

[27] R. J. Faber and G. K. Fraenkel, *J. Chem. Phys.*, 1967, **47**, 2462.

[28] J. Q. Adams, S. W. Nicksic, and J. R. Thomas, *J. Chem Phys.*, 1966, **45**, 654.