Electron Spin Resonance Studies. Part 71.[1] Side-chain Oxidation Pathways in the Reactions of $^{\bullet}OH$ and $SO_4^{-\bullet}$ with Some Phenyl-substituted Carboxylic Acids, their Anions, and Some Related Compounds

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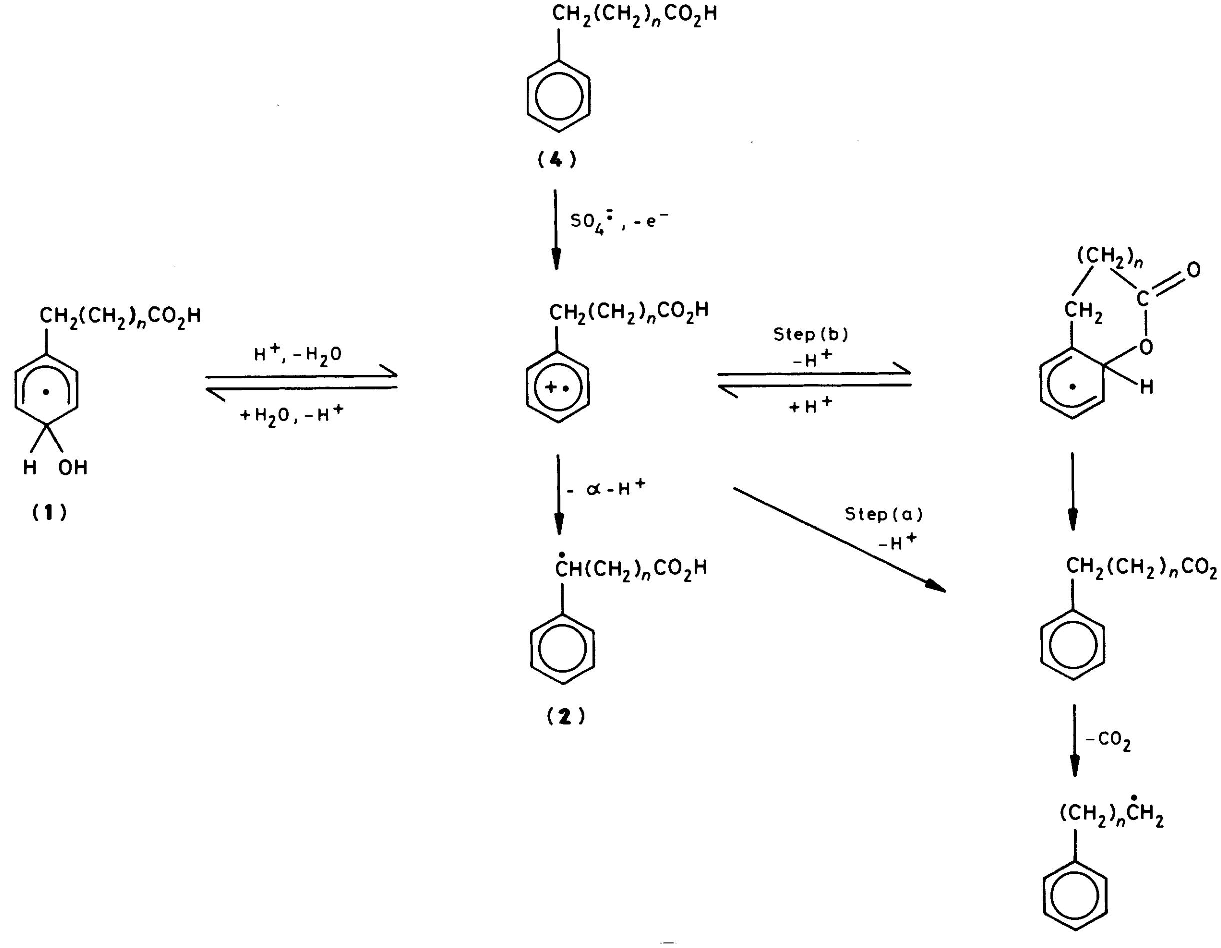
A series of arene radical-cations has been generated *in situ* by the reactions of methylbenzene, phenylethanoic acid, 3-phenylpropanoic acid, and some derivatives and cyclic analogues with both $SO_4^{-\bullet}$ and $^{\bullet}OH$ (the latter in acid solution). The results are interpreted in terms of a variety of subsequent rapid reactions including hydration, deprotonation (to give benzylic radicals), and fragmentation (decarboxylation): for a series of radical-zwitterions $^{+\bullet}Ar(CH_2)_nCO_2^-$ (n = 1—3) decarboxylation ($k \geqslant 10^9$ dm^3 mol^{-1} s^{-1}) appears to proceed *via* direct intramolecular electron-transfer, though in some cases formation of a discrete σ-bonded intermediate cannot be ruled out.

It has previously been shown[2,3] that, although the hydroxyl radical attacks aromatic rings more readily than it abstracts hydrogen from C–H or O–H bonds, side-chain oxidation [*e.g.* of $Ph(CH_2)_nCO_2H$, n = 2,3] is observed under acidic conditions. In a preliminary[3] study we showed that the mode of fragmentation is dependent upon pH (*e.g.* $PhCH_2CH_2CO_2H$ gives $PhCH_2CH_2^{\bullet}$ at pH *ca.* 3 but $^{\bullet}CHPhCH_2CO_2H$ at pH < 1.8), an observation which may be related to the multiplicity of 'remote' side-chain oxidation pathways reported for the reaction of related compounds with $SO_4^{-\bullet}$ (see *e.g.* ref. 4). It appears likely that loss of a benzylic hydrogen characterizes the deprotonation of an aromatic radical-cation (see Scheme 1) whereas oxidation elsewhere in the side-chain may occur, for example, *via* direct electron-transfer [step (a)] or *via* homolytic decomposition of a discrete σ-bonded cyclic intermediate [step (b)].

In an attempt to distinguish these possibilities and, in particular, to delineate the electronic and geometric factors which govern the modes of side-chain oxidation we have employed e.s.r. spectroscopy to monitor directly radicals produced from the reaction of a number of side-chain- and ring-substituted arylalkanoic acids with $^{\bullet}OH$ and $SO_4^{-\bullet}$.



Scheme 1.

Table 1. E.s.r. parameters of radicals detected during the oxidation of phenyl-substituted alkanoic acids by $^{\cdot}OH$[a,b]

		Hyperfine splittings (mT)[d]					
Substrate	Radical[c]	*a*(α-H)	*a*(β-H)	*a*(2-H)	*a*(3-H)	*a*(4-H)	*a*(other)
$PhCH_2CO_2H$	(**3**; *n* = 0)	1.62		0.50	0.17	0.62	
$Ph(CH_2)_2CO_2H$	(**3**; *n* = 1)	2.18	2.78				
	(**2**; *n* = 1)	1.67	1.47	0.50	0.17	0.60	
$PhCH_2CHMeCO_2H$	(**5**)	2.08	2.28(2) 2.44(3)				
	(**6**)	1.68	1.48	0.50	0.17	0.61	
$PhCHMeCH_2CO_2H$	(**7**)	2.14	2.78				
	(**8**)		1.47(2) 1.51(3)	0.50	0.17	0.60	
$Ph(CH_2)_3CO_2H$	(**3**; *n* = 2)	2.18	2.77				0.05 (2γ-H)
	(**2**; *n* = 2)	1.62	1.63	0.49	0.16	0.59	
$Ph(CH_2)_4CO_2H$	(**2**; *n* = 3)	1.58	1.47	0.50	0.17	0.61	

[a] Hydroxycyclohexadienyl adducts were also detected from each substrate (see text). [b] For details of pH range in which radicals are observed, see text. Data refer to acid solutions. [c] *g* 2.0026 (±0.0001). [d] ±0.01 mT.

Results and Discussion

The hydroxyl radical was generated *in situ* with the Ti^{III}–H_2O_2 couple [reaction (1)] in a continuous-flow system incorporating a three-way mixing chamber.[5] The sulphate radical-anion was generated both from the analogous reaction of the Ti^{III}–$S_2O_8^{2-}$ couple [reaction (2)] and also by the photolytic decomposition (with a 1 kW mercury–xenon lamp) of slowly flowing solutions containing potassium peroxydisulphate (with, in some cases, propanone as a co-solvent and photosensitizer).[6]

$$Ti^{III} + H_2O_2 \longrightarrow Ti^{IV} + {}^{\cdot}OH + OH^- \qquad (1)$$

$$Ti^{III} + S_2O_8^{2-} \longrightarrow Ti^{IV} + SO_4^{-\cdot} + SO_4^{2-} \qquad (2)$$

(a) *Reaction of Some Phenyl-substituted Alkanoic Acids.*—(i) *With* $^{\cdot}OH$. In the pH range 3.5—9.5 all the substrates studied (Table 1) gave rise to complex spectra from their reaction with $^{\cdot}OH$, as previously reported.[2] While these spectra could not be fully analysed, the principal features (the total width of typically *ca.* 6 mT and the large number of lines) are consistent with the formation of mixtures of the appropriate hydroxycyclohexadienyl radicals[2] [*e.g.* (**1**) in Scheme 1]; different isomers were not distinguished. Since the acids (**4**) have[7] pK_a *ca.* 4.6 it appears that both the acids and their anions undergo addition rather than side-chain oxidation. Under more acidic conditions it was found that, depending on the substrate and the pH, the spectra of hydroxycyclohexadienyl adducts were replaced by those of either (or both) alkyl radicals (**3**), resulting from decarboxylation and/or the appropriate benzylic radicals (**2**). The parameters (see Table 1) are consistent with previous analyses and assignments to alkyl and benzylic radicals (see *e.g.* ref. 2): the assignment of the spectrum from (**2**; *n* = 2) from 4-phenylbutanoic acid was confirmed by generating this radical by the addition of $^{\cdot}CH_2CO_2H$ (from $^{\cdot}OH$ and[8] ICH_2CO_2H) to phenylethene.

For phenylethanoic acid the spectrum of the benzyl radical began to replace those from hydroxycyclohexadienyl adducts at pH <2 and was the only signal observed at pH <1. 3-Phenylpropanoic acid gave increasingly strong signals from the decarboxylated radical (**3**; *n* = 1) rather than adducts as the pH was lowered below 3.5, but below pH *ca.* 1.8 these signals were in turn replaced by those from the benzylic radical (**2**; *n* = 1) (see *e.g.* Figure 1). The variation with pH in the relative concentrations of radicals detected is shown in Figure 2: the relative concentrations of the radicals formed by fragmentation were obtained by spectrum simulation, and the corresponding quantitative behaviour of the particularly complex spectra from the hydroxycyclohexadienyl adducts (not individually assigned) was estimated on the basis of the growth (with pH) of individual lines (and on the assumption of a constant total radical concentration). Like 3-phenylpropanoic acid, 2-methyl-3-phenylpropanoic acid gave a dominant signal from (**5**) at pH 2.5 and from (**6**) below pH 1.5, and 3-phenylbutanoic acid gave dominant signals attributed to (**7**) and (**8**) under similar conditions.

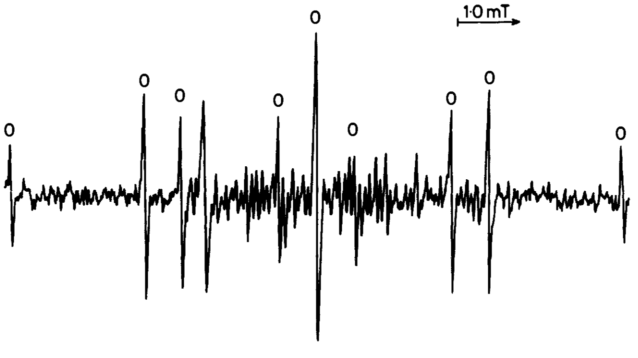


Figure 1. E.s.r. spectrum of the phenethyl radical (**3**; *n* = 1) (0) and the benzylic radical (**2**; *n* = 1) formed in the reaction between $^{\cdot}OH$ and 3-phenylpropanoic acid at pH 1.0

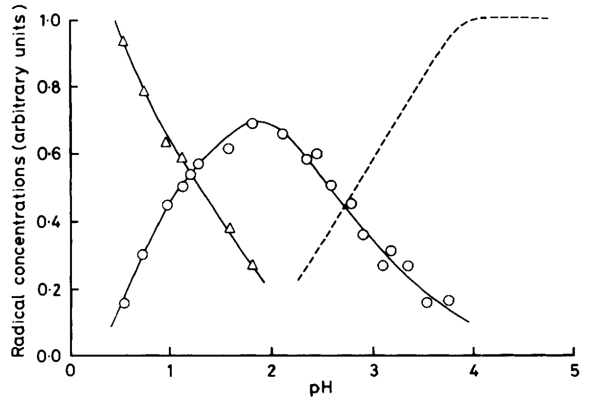
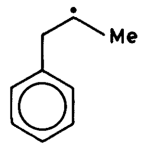


Figure 2. Variation with pH in the relative steady-state concentrations of (**3**; *n* = 1) (○) and (**2**; *n* = 1) (△) in the reaction between $^{\cdot}OH$ and 3-phenylpropanoic acid: the dotted line indicates the estimated total concentration of hydroxycyclohexadienyl adducts detected at higher pH (see text)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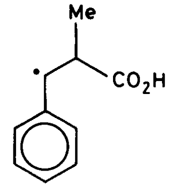
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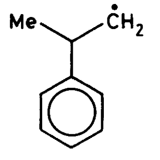
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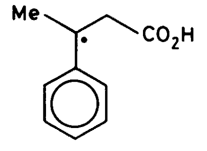
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4-Phenylbutanoic acid gave essentially similar results though the signals were generally weaker than those for 3-phenylpropanoic acid; as the pH was lowered, signals from (3; $n = 2$) were first observed at pH *ca.* 3.5, with the signals from (2; $n = 2$) becoming noticeable by pH *ca.* 2.5 and growing in intensity at the expense of (3; $n = 2$) as the pH was lowered. With 5-phenylpentanoic acid, in contrast, the spectra of hydroxyl adducts persisted until pH *ca.* 1.5, below which a weak spectrum of (2; $n = 3$) was detected: there was no evidence for decarboxylation for this substrate. We were similarly unable to obtain any evidence for acid-catalysed decarboxylation of the esters $Ph(CH_2)_nCO_2Me$ ($n = 1$ and 2), for which weak complex signals characteristic of hydroxycyclohexadienyl radicals were observed down to pH *ca.* 1: below this pH loss of an α-hydrogen (as with the acids) cannot be ruled out.

The results for the acids $PhCH_2(CH_2)_nCO_2H$ ($n = 0$—2) bear a close resemblance to those observed[2,3] for some related alcohols under similar conditions: thus $^{\bullet}OH$ adducts of benzyl alcohol are replaced by $^{\bullet}CHPhOH$ below pH 1.5, those from $PhCH_2CH_2CH_2OH$ give $^{\bullet}CH(OH)CH_2CH_2Ph$ (<pH 3) then $^{\bullet}CHPhCH_2CH_2OH$ (<pH 1.5) whereas $Ph(CH_2)_4OH$ gives solely $^{\bullet}CHPh(CH_2)_3OH$.

Our observations indicate that attack of $^{\bullet}OH$ occurs preferentially at the ring, that at very low pH acid-catalysed decomposition occurs for all substrates with resultant breakage of a C_α-H bond, or, for phenylethanoic acid, the C_α-C bond, and that decarboxylation apparently only results (at intermediate pH) for those acids (or anions) with n 0—2 (*i.e.* in which the ring and the carboxylate group are in reasonable proximity).

(ii) *With* $SO_4^{-\bullet}$. It is generally believed[9,10] that reaction of aromatic compounds with the sulphate radical-anion proceeds *via* the formation (possibly *via* a very short-lived intermediate[11]) of a radical-cation, a species which has also been detected optically in the reaction between $^{\bullet}OH$ and alkylbenzenes at low pH.[9,12] We investigated the possibility that such species are likewise involved in the acid-catalysed decomposition of hydroxycyclohexadienyl species described above by studying the behaviour of the same substrates during their oxidation with $SO_4^{-\bullet}$, a reaction which might thus be expected to have features in common with those described for $^{\bullet}OH$.

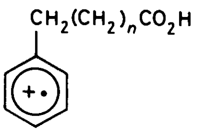
Radicals were readily detected from the reaction of the Ti^{III}–$S_2O_8^{2-}$ redox couple with the phenyl-substituted carboxylates from pH 6 up to *ca.* 9.5.* For example, phenylethanoate, 3-phenylpropanoate, 2-methyl-3-phenylpropanoate, 3-phenylbutanoate, and 4-phenylbutanoate gave solely the decarboxylated radicals (3; $n = 0$), (3; $n = 1$), (5), (7), and (3; $n = 2$) respectively; signals were relatively weak for the last-named compound. 5-Phenylpentanoate gave a weak and complex spectrum (probably from cyclohexadienyl adducts) with no trace of the corresponding decarboxylated radical.

No signals were detected below pH *ca.* 6 using the Ti^{III}–$S_2O_8^{2-}$ couple [which may reflect a reduction in the rate of reaction (2) at lower pH] so an alternative photolytic method of generation was employed. Radicals were detected in this way from phenylethanoic, 3-phenylpropanoic acid, and 4-phenylbutanoic acid: oxidation of the first substrate resulted in the detection of the benzyl radical (over the pH range 0.5—9.5), whereas for the second, signals from (3; $n = 1$), observed as the only species present in the pH range 2—9 (*cf.* reaction of Ti^{III}–$S_2O_8^{2-}$), were steadily replaced below pH *ca.* 2 by those from (2; $n = 1$). The change in relative concentrations of (3; $n = 1$) and (2; $n = 1$) below pH 2 mirrored exactly those for the same radicals generated from this substrate with $^{\bullet}OH$ in the same pH range (Figure 1).

4-Phenylbutanoic acid reacted with $SO_4^{-\bullet}$ under these conditions to give signals from (3; $n = 2$) above pH *ca.* 3 (the signals were particularly intense at high pH); below this pH the increase in complexity and decrease in overall signal height which accompanies the disappearance of (3; $n = 2$) is attributed to formation of (2; $n = 2$).

Attempted photolytic oxidation of other acids listed in Table 1 led to the deposition of an intractable solid on the walls of the flow cell and the concomitant detection of a broad, featureless signal which obscured all other signals: these reactions were not further investigated. Only weak and complex signals (from hydroxyl adducts and/or loss of an α-hydrogen) could be detected from the esters $Ph(CH_2)_nCO_2Me$ ($n = 1, 2$); there was no evidence for cleavage of the CH_2–CO bond.

The detection of (2; $n = 1$—3) in the reactions of the parent acids or anions with $SO_4^{-\bullet}$ [and in particular, the evidence that this represents the only pathway for the longer-chain substrate (4; $n = 3$)] confirms that initial attack takes place on the aromatic ring (probably to give a radical-cation): subsequent partition may then occur between deprotonation and, for shorter chains, decarboxylation. The loss of an α-proton resembles the behaviour of aromatic substrates with $^{\bullet}OH$ at very low pH: where exact comparison is possible (3-phenylpropanoic acid), precisely the same behaviour is observed. This strongly supports the suggestion that acid-catalysed decomposition of $^{\bullet}OH$ adducts and reaction with $SO_4^{-\bullet}$ give a common intermediate, which we believe to be the aromatic radical-cation.† The effect of acid in inducing deprotonation rather than decarboxylation may then be interpreted in several ways. First, if decarboxylation occurs *via* direct electron-transfer (from CO_2H or CO_2^- to the ring) then it would be anticipated that this would occur more readily from the carboxylate anion (a radical-zwitterion) (10) than from (9).



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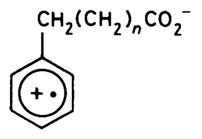

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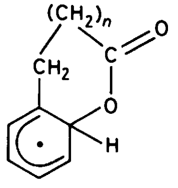

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* The upper limit of our study is imposed by the rapidity of the reaction of $SO_4^{-\bullet}$ with OH^- and subsequent effective generation of $^{\bullet}OH$ at pH >9.5.[13]

† Rapid deprotonation as a pathway for decomposition of aromatic radical-cations with aliphatic side-chains is well established: a value of k *ca.* 10^7 s^{-1} has been reported for the reaction of the methylbenzene radical-cation (see also later).[12]

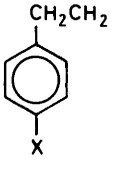
Table 2. E.s.r. parameters of radicals detected from the reaction of $4\text{-}XC_6H_4CH_2CH_2CO_2H$ with $^{\bullet}OH$ and $SO_4^{-\bullet}$

			Hyperfine splittings (mT)^b				
X	Reaction conditions^a	Radical	a(α-H)	a(β-H)	a(2-H)	a(3-H)	Other
Cl	A,^{c}B,C	(**12**; X = Cl)	2.20	2.89			
	A,^{c}C	(**13**; X = Cl)	1.62	1.64	0.50	0.17	0.49 (^{37}Cl), 0.53 (^{35}Cl)^d
Me	A,^{c}B	(**12**; X = Me)	2.20	2.94			
	A^c	(**13**; X = Me)	1.64	1.65	0.51	0.17	0.66 (3 H, Me)
HO	A,^{c}B,C	$^{\bullet}OC_6H_4CH_2CH_2CO_2H^e$			0.62	0.15	0.68 (2 H, CH_2)

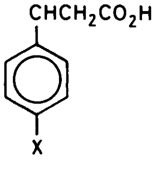
^{a} A $^{\bullet}OH$ (from Ti^{III}–H_2O_2). B $SO_4^{-\bullet}$ (from $S_2O_8^{2-}$–Ti^{III}). C $SO_4^{-\bullet}$ (photolysis). ^{b} ±0.01 mT. All radicals had g 2.0026 except where stated. ^{c} Hydroxycyclohexadienyl radicals also detected under mildly acidic and alkaline conditions. For pH-dependence behaviour, see text. ^{d} g 2.0035. ^{e} g 2.0047.

Secondly, it is conceivable that the overall electron-transfer occurs *via* the formation and decomposition of a bicyclic species, *e.g.* (**11**);* this should be formed more readily from the nucleophilic carboxylate ion (and where n is 1 or 2, rather than 3). Thirdly, the effect of acid may be to provide alternative heterolytic decomposition of (**11**) in competition with homolysis (see Scheme 1). Lastly, at least for the reactions of hydroxyl, the observation of decarboxylation could reflect formation of, *e.g.* (**11**), from an adduct (rather than a cation-radical) in which departure of the leaving group (H_2O) is assisted by internal nucleophilic attack by the carboxylate group. The behaviour of a number of ring-substituted derivatives of 3-phenylpropanoic acid and phenylethanoic acid (and some analogues with other side-chains) was explored in an attempt to distinguish these possibilities.

(b) *Oxidation of Some Ring-substituted Aromatic Alkanoic Acids.*—(i) *Substituted* 3-*phenylpropanoic acids.* Oxidation of 3-(4-chlorophenyl)propanoic acid with $^{\bullet}OH$ gave hydroxy adducts (pH > *ca.* 3.5), the appropriate decarboxylated radical (**12**; X = Cl) (in the pH range 3.5—*ca.* 1.0) and the benzylic radical (**13**; X = Cl) (pH < 1.5); with $SO_4^{-\bullet}$ (**12**; X = Cl) was detected down to pH *ca.* 1.5, below which these signals were also replaced by those from (**13**; X = Cl) (for e.s.r. data, see Table 2). The behaviour mirrors that of the unsubstituted acid (Figure 1) except that the pH at which signals from (**12**; X = Cl) and (**13**; X = Cl) are equal in intensity was *ca.* 1.0, rather than 1.2. With 3-(4-methylphenyl)propanoic acid, $^{\bullet}OH$ similarly gave adducts (>3.5), then (**12**; X = Me) in the pH range 3.5—2.5, and (**13**; X = Me) as the only radical clearly detected below pH *ca.* 2.5 [the formation of low concentrations of radical (**14**), whose formation might also have been expected, could not be ruled out]. Radical (**12**; X = Me) was also formed by reaction of the corresponding anion with $SO_4^{-\bullet}$ (*via* Ti^{III}–$S_2O_8^{2-}$) but no signals could be detected at low pH under flow or photolytic conditions. As with the 4-chloro substituent, the pH at which decarboxylation becomes effective is unaltered, though the pH for the formation of the benzylic radical is now higher than for the unsubstituted analogue. Closely similar behaviour was also observed for 3-(2-methylphenyl)propanoic acid: with $^{\bullet}OH$ the radical $^{\bullet}CH_2CH_2Ar$ (Ar = $2\text{-}MeC_6H_4$) was detected in the pH range 3.5—2.5, below which a mixture of radicals attributed to the two possible benzyl radicals was formed, and with $SO_4^{-\bullet}$ in the pH range 6—9 decarboxylation was observed.



(**12**)



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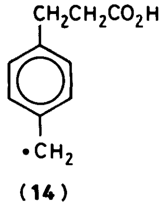

(**14**)

In the reaction of $4\text{-}NO_2C_6H_4CH_2CH_2CO_2H$ the only signals detected from either Ti^{III}–H_2O_2 or Ti^{III}–$S_2O_8^{2-}$ systems were those obtained from the corresponding radical-anion (at pH >6) [a(N) 1.10, a(2-H) 0.33, a(3-H) 0.11, a(4-CH_2) 0.24 mT, g 2.0045, *cf.* ref. 14]; its generation probably involves one-electron transfer[15] from the radical $^{\bullet}CH[N(CH_2CO_2H)_2]$-$CH_2N(CH_2CO_2H)_2$ formed by reaction of both $^{\bullet}OH$ and $SO_4^{-\bullet}$ with the sequestering agent EDTA.

3-(4-Hydroxyphenyl)propanoic acid gave $^{\bullet}OH$ adducts at pH > *ca.* 4, but no signals were detectable as the pH was further reduced until the corresponding phenoxyl radical[16] was clearly observed below pH 1.5. In contrast, with $SO_4^{-\bullet}$ in the photolytic system the phenoxyl radical was detected throughout the pH range 0.5—9.0. This suggests that the appropriate radical cation (*e.g.* as formed from $SO_4^{-\bullet}$) readily deprotonates (*via* proton loss from oxygen rather than α-carbon): failure to detect signals in the $^{\bullet}OH$ reaction between pH *ca.* 4 and 1.5 suggests that the radical-cation, generated by acid-catalysed loss of OH^-, is readily reduced under these conditions by Ti^{III} (as claimed previously for the anisole radical-cation[17]). The formation of the phenoxyl radical from $^{\bullet}OH$ at pH < *ca.* 1.5 may then well reflect the reaction of an $^{\bullet}OH$ adduct (*e.g.* the *ipso* isomer) which does not proceed through a radical-cation:[18] this aspect of the reaction will not be discussed further here.

With 3-(4-methoxyphenyl) propanoic acid no signals were detected in the reaction either of $^{\bullet}OH$ (which, as with anisole and phenol in an intermediate pH-range may reflect ready formation and reduction of a radical-cation) or $SO_4^{-\bullet}$.

(ii) *Substituted phenylethanoic acids.* Reaction of $4\text{-}XC_6H_4$-CH_2CO_2H (X = Me, Cl, F) with $^{\bullet}OH$ gave hydroxycyclohexadienyl adducts and, as the pH was lowered, the appropriate benzyl radicals (**15**) formed *via* decarboxylation: Table 3 gives the hyperfine splittings of radicals (**15**) together with the pH at which the concentration of adducts was found to be approximately equal to that of (**15**). It is notable that with X = Cl and F this pH is somewhat less than for the unsubstituted analogue (0.9 and 0.7 respectively compared with pH *ca.* 1.5), whereas for Me (pH 2.2) the pH is somewhat raised. Reaction of $4\text{-}MeOC_6H_4CH_2CO_2H$ with $^{\bullet}OH$ gave clearly detected signals of the appropriate benzyl radical below pH *ca.* 4; above this, signals were obscured by those derived from the radical formed from EDTA. With $SO_4^{-\bullet}$ (generated photolytically) the appropriate benzyl radicals were the only species detected in the pH range 0.5—9.

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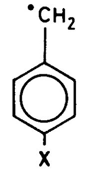
* An alternative five-membered ring (an *ipso* adduct) rather than, or as well as, that depicted may be involved: *cf.* ring-closure of the radical-cations of hex-4-enoic acid and hex-4-enol in the 5-*exo* mode.[1]

Table 3. E.s.r. parameters of radicals detected from reaction of 4-$XC_6H_4CH_2CO_2H$ with $^{\bullet}OH$ and $SO_4^{-\bullet}$

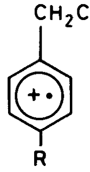
			Hyperfine splittings (mT)[b]					
X	Reaction conditions[a]	Radical	a(α-H)	a(2-H)	a(3-H)	Other	g	pH[c]
F	A,[d]B,C	(**15**; X = F)	1.63	0.53	0.17	1.40 (^{19}F)	2.0067	0.7
Cl	A,[d]B,C	(**15**; X = Cl)	1.61	0.52	0.18	0.50 (^{37}Cl), 0.53 (^{35}Cl)	2.0036	0.9
Me	A,[d]B,C	(**15**; X = Me)	1.60	0.51	0.16	0.68 (3 H, Me)	2.0025	2.2
OMe	A,[d]B	(**15**; X = OMe)	1.59	0.51	0.16	0.07 (3 H, OMe)	2.0030	>4.0[e]
OH	A,[d]B,C	$\bullet OC_6H_4CH_2CO_2H$		0.61	0.14	1.25 (β-CH_2)	2.0048	[e]

[a] A $^{\bullet}OH$ (from Ti^{III}–H_2O_2). B $SO_4^{-\bullet}$ (from $S_2O_8^{2-}$–Ti^{III}). C $SO_4^{-\bullet}$ (photolytically). [b] ±0.01 mT. [c] pH values at which the hydroxyl adducts (in the experiment with $^{\bullet}OH$) are half-removed (being partially replaced by signals from the decarboxylated species). [d] Hydroxycyclohexadienyl adducts obtained under alkaline and mildly acid conditions. [e] See text.

From the relatively high pH value at which the adducts of 4-methoxyphenylethanoate fragment it appears that these are considerably more susceptible to acid-catalysed fragmentation than those of the unsubstituted analogue; however, this may also reflect in part an increased rate of generation of the radical-cation (**16**; R = OMe) as a result of the expected stability conferred upon it by the electron-donating methoxy group (see later). These observations and interpretation are consistent with the finding[19] that generation of $SO_4^{-\bullet}$ by pulse radiolysis and reaction with anisole gives the anisole radical-cation ($\lambda_{max.}$ 430 nm) directly and that the hydroxycyclohexadienyl adduct of anisole is believed to decay by an acid-catalysed process (*k ca.* 10^9 dm^3 mol^{-1} s^{-1}) to give the same species.



(**15**)

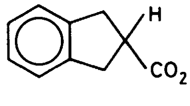


(**16**)

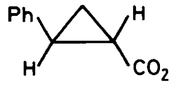
Whereas reaction of 4-nitrophenylethanoic acid with $OH^{\bullet}$ gave only detectable signals from the corresponding anion-radical [a(N) 1.08, a(2-H) 0.34, a(3-H) 0.11, a(4-CH_2) 0.40 mT, g 2.0045], as with its longer-chain analogue, oxidation of 4-hydroxyphenylethanoic acid with $^{\bullet}OH$ gave hydroxyl adducts and then the appropriate phenoxyl radical (below pH *ca.* 2.4), which was also detected through the pH range with $SO_4^{-\bullet}$. There was no evidence for decarboxylation or loss of a benzylic proton.

(iii) *Methylbenzene and some* 4-*substituted derivatives.* Oxidation of 4-chloromethylbenzene with $^{\bullet}OH$ led to weak spectra from hydroxycyclohexadienyl radicals which were replaced by pH *ca.* 1 by those from (**15**; X = Cl). This behaviour mirrors that of methylbenzene itself (*cf.* ref. 2) and 1,4-dimethylbenzene, for which we found that reaction of $^{\bullet}OH$ gave benzyl radicals below pH *ca.* 2.5, with [adducts] ≃ [(**15**; X = H, Me)] at *ca.* 1.7 and 2.2, respectively. Though oxidation of 4-methoxymethylbenzene failed to yield a detectable radical throughout the pH range examined and 4-nitromethylbenzene gave only signals from the corresponding radical-anion [with a(N) 1.08, a(2-H) 0.34, a(3-H) 0.11, a(4-CH_3) 0.40 mT, g 2.0045], reaction of 4-hydroxymethylbenzene with $^{\bullet}OH$ gave adducts and also the corresponding phenoxyl radical [a(2-H) 0.61, a(3-H) 0.14, a(4-CH_3) 1.25 mT, g 2.0047] below pH *ca.* 3.0. Although reaction of $SO_4^{-\bullet}$ (generated both in the flow system and photolytically) gave only rather weak unanalysed signals with 1,4-dimethylbenzene and 1-chloro-4-methylbenzene, methylbenzene reacted to give detectable signals from the benzyl radical below pH *ca.* 2, and 1-hydroxy-4-methylbenzene gave the corresponding phenoxyl radical throughout the accessible pH range.

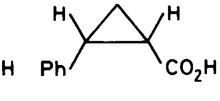
(c) *Oxidation of Some Phenyl-substituted Cyclic Alkanoic Acids.*—In order to probe the influence, if any, of geometrical factors upon the loss of the carboxy group in 3-phenylpropanoic acid and its derivatives, we studied the corresponding reactions of 2,3-dihydro-1*H*-indene-2-carboxylic acid (**17**) and the *E*- and *Z*-isomers of 2-phenylcyclopropanecarboxylic acid [(**18**) and (**19**), respectively].



(**17**)

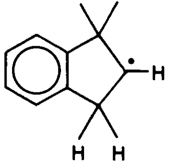


(**18**)

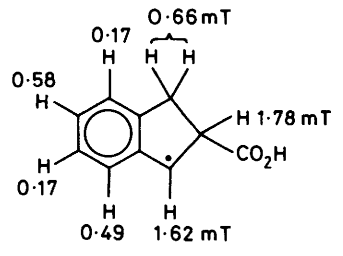


(**19**)

Oxidation of (**17**) with $^{\bullet}OH$ at pH *ca.* 9 resulted in the detection of a complex spectrum with a total width of *ca.* 6.5 mT, consistent with the formation of hydroxycyclohexadienyl adducts. This spectrum remained unchanged as the pH was lowered until *ca.* 3.8, when it was accompanied (and ultimately replaced) by a spectrum with a(H) 2.13, a(4H) 3.70 mT, g 2.0026 (the spectra had similar overall intensities at pH *ca.* 3.5). The new species is assigned structure (**20**) on account of the single α-proton splitting and the large interaction characteristic of β-proton splittings in a five-membered ring.[20] By pH 1.8 a spectrum attributed to (**21**) was first observed, with assignments as indicated; its intensity grew at the expense of (**20**) (with [(**20**)] ≃ [(**21**)] at pH 1.5) and it was the only species detectable below pH 0.7. Oxidation of (**17**) with the Ti^{III}–$S_2O_8^{2-}$ couple gave (**20**) in the pH range 6—9.5: no radical could be detected in the corresponding photolytic oxidation, in which an intractable deposit was formed in the flow cell.



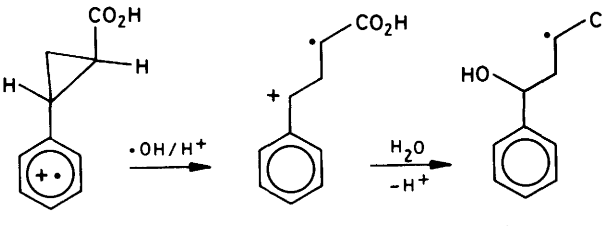
(**20**)



(**21**)

These results are closely similar to those observed in the reaction of 3-phenylpropanoic acid (and its *ortho*- and *para*-substituted analogues): decarboxylation and loss of α-H (with OH) occur over a similar pH range. This suggests that the mechanisms of reaction are similar in these cases and indicates that formal bonding between the ring and the carboxy group [as indicated as a possibility in Scheme 1(a)] is unlikely to be a requirement, since such an intermediate formed from (**17**) would be expected to be extremely strained.

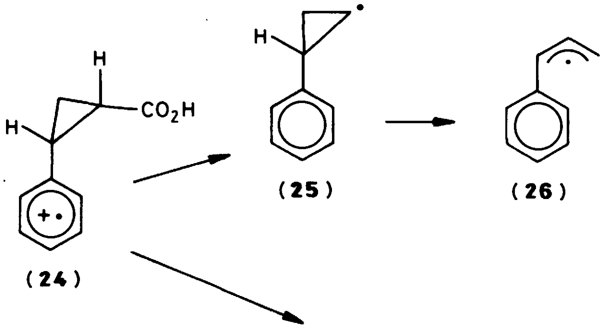
Oxidation of (**18**) with ˙OH led to the detection of adducts and, below pH 1.7, a spectrum with *a*(1H) 2.73, *a*(1H) 2.69, *a*(1H) 2.18 mT, and *g* 2.0033. These parameters characterize a carboxy-conjugated radical with non-equivalent β-proton splittings (typical of those adjacent to an asymmetric centre at the γ-carbon[21]). The conclusion that this is attributed to (**23**) which could result from ring-opening and subsequent solvolysis of a radical-cation [reaction (3)] is supported by the generation of an identical spectrum by the addition of ˙CH(OH)Ph (from benzyl alcohol and Ti^{III}–H_2O_2 at pH *ca.* 1) to propenoic acid. The pH at which the signals from the ˙OH adducts of (**18**) fall below the detectable limit is approximately the same as that observed for the corresponding adduct of *e.g.* 5-phenylpentanoic acid as well as methylbenzene and its counterparts, which suggests that the carboxy group plays no part in the fragmentation of the adducts (as would be expected from the geometry of the molecule).



(3)

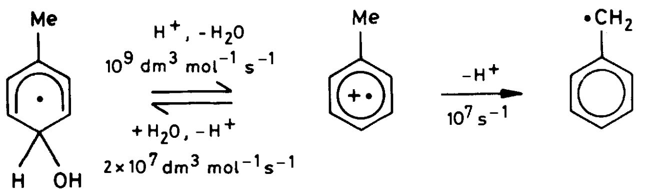
(**22**) (**23**)

Spectra from adducts and from (**23**) were also obtained from the *Z*-isomer (**19**) and ˙OH, but in marked contrast with (**18**) the spectrum attributed to (**23**) was clearly detected at pH *ca.* 3.5 and below: it was also accompanied in the pH range 3.5—1.7 by a spectrum with a considerable number of lines which is consistent with a delocalized structure: we tentatively suggest that this is from (**26**) derived by rapid ring-opening of the decarboxylated radical (**25**). Such behaviour resembles closely that of 3-phenylpropanoic acid and 4-phenylbutanoic acid (rather than the *E*-isomer) which suggests that a requirement for the enhanced rate of fragmentation of the ˙OH adducts or radical-cations from the former group of compounds is the ability of the carboxy group to take up a position relatively close to the aromatic ring. No signals could be obtained from either (**18**) or (**19**) with $SO_4^{-\cdot}$ under either flow or photolysis conditions.



(**24**) (**25**) (**26**) (**23**)

(d) *Mechanistic and Kinetic Implications.*—From the results for $SO_4^{-\cdot}$ and a variety of substrates at higher pH, it appears that the ease of subsequent fragmentation pathways of the radical-cations (or radical-zwitterions) decreases in the following order; loss of H^+ from phenolic OH > decarboxylation (α-, β-carboxy) > decarboxylation (γ-carboxy) > deprotonation (loss of α-C–H). For the radical-cations from carboxylic acids at low pH, it appears that only for phenylethanoic acid and its derivatives is decarboxylation faster than deprotonation *via* loss of α-C–H. We also note that these processes may in general be in competition with other reactions including, *e.g.*, dimerization and hydration of first-formed radical-cations. The methylbenzene radical-cation, for example, has been directly detected during pulse radiolysis experiments involving ˙OH (in acid) and the one-electron oxidant $SO_4^{-\cdot}$;[9,12] it is suggested that deprotonation (*k ca.* 10^7 s^{-1}) is in competition with hydration of the radical cation (*k* 2×10^7 dm^3 mol^{-1} s^{-1}; see Scheme 2), since hydroxyl adducts can be detected in reactions of $SO_4^{-\cdot}$ in neutral solution.* This Scheme is taken as the basis for kinetic and mechanistic analysis (see later).



Scheme 2.

The decarboxylation reactions brought about by $SO_4^{-\cdot}$ evidently involve an interaction, between the radical-cation centre on the ring and the CO_2^- groups, which clearly decreases when the sites are well separated [*e.g.* in 5-phenylpentanoic acid and (**18**)]. Although the formation of a discrete σ-bonded intermediate (Scheme 1) would account for these observations [and for the formation of cyclic compounds during the apparently analogous oxidation of related compounds with Tl^{3+} (*cf.* ref. 22)], the ease of reaction of the cyclic acid (**17**) suggests that a formal bond is not required for overall transfer. Long-range electron-transfer from either the carboxylate oxygen or the C_β–C_γ bond is implied. The observation that as the pH is lowered decarboxylation of *e.g.* (**17**) and $PhCH_2CH_2CO_2H$ gives way to loss of an α-proton would then be consistent with the slower rate of transfer from the carboxylic acid than the carboxylate groups. {We cannot rule out the production from acyclic acids of a cyclized intermediate which is either formed more slowly from the acid than the anion or reconverted into the radical-cation at lower pH [Scheme 1, step (b).]}

Results for ˙OH clearly have much in common with those for $SO_4^{-\cdot}$ especially in the decarboxylation reaction observed and in the results at very low pH where, for example, decarboxylation gives way to deprotonation. [Any major difference observed (*e.g.* for some of the methoxylated compounds) seems likely to reflect the destruction by Ti^{III} of radical-cations in the ˙OH reaction.] It follows that radical-cations are also involved in the ˙OH reactions (certainly at low pH, possibly also at intermediate pH values). However, what remains to be explored is the nature of the factors which govern the pH at which adducts are replaced for a given substrate: contrast, for example, the fragmentation of hydroxyl adducts of methylbenzene (loss of water and a proton) and phenylethanoic acid (loss of water, CO_2, and a proton) at pH *ca.* 2 whereas 3-phenylpropanoic acid

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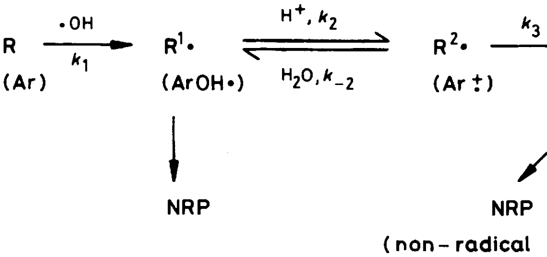
* Such adducts were not observed in the present work: this may reflect their ready oxidation (*e.g.* by $S_2O_8^{2-}$), the weakness of the appropriate resonances (which would be a mixture of multi-lined spectra), or their lack of involvement. However, in experiments with $SO_4^{-\cdot}$ and methylbenzene, the lack of detection of $PhCH_2^{\cdot}$ as the pH is lowered until pH *ca.* 2 is reached is in broad agreement with the mechanism shown in Scheme 2.

and 4-methoxyphenylethanoic acid are decarboxylated at pH *ca.* $\geqslant 3.5$

Our approach has entailed employing simple steady-state analysis as well as the results of more detailed analysis with a kinetic simulation program. As has been previously pointed out, the radicals detected by e.s.r. spectroscopy in experiments with the $\mathrm{Ti^{III}}$–H_2O_2 flow system are those formed inside the cavity and a pseudo-steady-state analysis is applicable.[23]



Scheme 3.

Scheme 3 shows the simplest scheme employed, in which the substrate (R) reacts with $^{\bullet}$OH to give an adduct (R^1) which can undergo acid-catalysed loss of water to a radical-cation R^2 (and be regenerated from it *via* hydration); R^3 is formed *via* deprotonation or decarboxylation of the radical-cation R^2. It is assumed that radicals R^1 and R^3 are destroyed (by dimerization and cross-termination) to give non-radical products (with $2k_t$ *ca.* 10^9 dm^3 mol^{-1} s^{-1}) whereas R^2, present in much lower concentrations, is removed solely by first-order decomposition.

Steady-state analysis for $[\mathrm{R}^{2\bullet}]$ and $[\mathrm{R}^{3\bullet}]$ leads to the following expression for the ratio of the radicals $[\mathrm{R}^{1\bullet}]$ and $[\mathrm{R}^{3\bullet}]$, *i.e.* those radicals which are detected by e.s.r. spectroscopy and whose relative concentrations are critically dependent upon pH [equation (4)]. In the special case when $k_{-2}[H_2O] < k_3$, this reduces to equation (6) where $\mathrm{R_{tot}}$ is the total concentration of radicals detected by e.s.r. ($[\mathrm{R}^{1\bullet}] + [\mathrm{R}^{3\bullet}]$). Several different patterns of behaviour are suggested by our results, which are analysed accordingly.

$$\frac{[\mathrm{R}^{1\bullet}]}{[\mathrm{R}^{3\bullet}]} = \left\{\frac{k_{-2}}{k_3}[H_2O] + 1\right\} 2k_t \frac{\{[\mathrm{R}^{1\bullet}] + [\mathrm{R}^{3\bullet}]\}}{k_2[H^+]} \quad (4)$$

$$\frac{[\mathrm{R}^{1\bullet}]}{[\mathrm{R}^{3\bullet}]} = \frac{2k_t\{[\mathrm{R}^{1\bullet}] + [\mathrm{R}^{3\bullet}]\}}{k_2[H^+]} \quad (5)$$

$$= \frac{2k_t[\mathrm{R_{tot}}]}{k_2[H^+]} \quad (6)$$

(i) *Reaction of* $^{\bullet}$*OH with phenylethanoic acid, its anion, and derivatives.* Since throughout the accessible pH range the reactions of $PhCH_2CO_2H$ and its ring-substituted derivatives with $SO_4^{-\bullet}$ give solely the (decarboxylated) benzyl radicals (following attack at the ring) we conclude that loss of CO_2 (or CO_2 and H^+) from R_2 (the radical-cation) is much faster than rehydration (Scheme 3). Thus $k_3 > k_{-2}[H_2O]$. It follows that, in the experiments with $^{\bullet}$OH, there is no effective rehydration and that the pH at which adducts are converted into benzyl radicals reflects the formation of the radical-cation as the slow step. Equations (5) and (6) should then hold: taking $2k_t$ as 10^9 dm^3 mol^{-1} s^{-1} and $[^{\bullet}\mathrm{R_{tot}}]$ as 4×10^{-6} mol dm^{-3} (as observed) it follows that $[\mathrm{R}^{1\bullet}]/[\mathrm{R}^{3\bullet}] = 4 \times 10^3/k_2[H^+]$, and that when $[\mathrm{R}^{1\bullet}] = [\mathrm{R}^{3\bullet}]$, k_2 is given by $(4 \times 10^3)[H^+]^{-1}$.

The values of k_2 calculated using this method for a variety of substituted phenylacetic acids $4\text{-}XC_6H_4CH_2CO_2H$ (from the data given in Table 3) are as follows: $>4 \times 10^7$ (X = MeO), 6.6×10^5 (Me), 1.3×10^5 (H), 3.2×10^4 (Cl) and 2.1×10^4 (F), dm^3 mol^{-1} s^{-1}. Use of a kinetic simulation program in which were included details of the radical generation method (with experimental values of $[\mathrm{Ti^{III}}]$ and $[H_2O_2]_0$, and $k_{\mathrm{Ti^{III}}+H_2O_2}$ taken as 2×10^3 dm^3 mol^{-1} s^{-1}; ref. 24), the rate of attack of $^{\bullet}$OH on the ring (taken as[25] 10^9 dm^3 mol^{-1} s^{-1}), and a 'mixing time' of 0.040 s, led to the prediction both of $[\mathrm{R_{tot}}]$ *ca.* 4×10^{-6} mol dm^{-3} (as observed) and of replacement of R^1 by R^3 as pH was changed exactly as expected.

These results show that the rate of the acid-catalysed loss of OH^- from the adduct is dramatically encouraged by the ($+M$) methoxy group but retarded by electron-withdrawing groups, as would be expected if the rate-determining step in this reaction is indeed the production of a radical-cation.

It has been reported that k_2 for the formation of methylated benzene radical-cations from the $^{\bullet}$OH adducts is *ca.* 10^9 dm^3 mol^{-1} s^{-1}.[12] It follows first that the carboxylic acid group in $PhCH_2CO_2H$ significantly retards the acid-catalysed loss of hydroxy (compared with methylbenzene), evidently on account of its electron-withdrawing effect. Secondly, if we assume that hydration of $^{+\bullet}PhCH_2CO_2H$ is at least as fast as for $^{+\bullet}PhMe$, then it follows the rate constant for the decarboxylation of the phenylethanoic acid radical-cation is $>10^9$ s^{-1}.

(ii) *Deprotonation of radical-cations from methylbenzene and related species.* If we accept that the acid-catalysed loss of OH^- from the hydroxyl adduct of methylbenzene is extremely rapid (k *ca.* 10^9 dm^3 mol^{-1} s^{-1}) and that hydration is also possible (as depicted in Scheme 2) it follows that the pH at which benzyl replaces adducts in steady-state experiments with this substrate is governed by the competition between hydration and deprotonation [*i.e.* according to equation (4) rather than (5) and (6)]. If we employ values of k_{-2} and k_3 as reported (Schemes 2 and 3, *i.e.* with $k_{-2}[H_2O]/k_3$ *ca.* 10^2) then both using the simple model employed to give equation (4) and using the kinetic simulation program leads to the conclusion that benzyl radical should replace the adducts by pH *ca.* 3.5, rather than at *ca.* 2 as observed. The experimental result can be effectively simulated however if the ratio of the rate constants for rehydration to deprotonation is such that $k_{-2}[H_2O]/k_3$ is *ca.* 2.5×10^3, *i.e.* that k_{-2}/k_3 is *ca.* 50 dm^3 mol^{-1}, and that hydration is (relatively) more important than suggested. We note that an adjusted value of *ca.* 10^6 s^{-1} (for deprotonation), together with 2×10^7 dm^3 mol^{-1} s^{-1} (for hydration), would be more in line with those reported for radical-cations derived from xylenes.[12] If such an interpretation (with modified rate constant) is correct then it also follows that adducts seen in the pH range 2—3.5 are largely formed *via* rehydration of the radical-cation rather than direct attack: the complexity of the spectra render detailed analysis impossible for substrates studied here but for certain other aromatic compounds (thiophene and its derivatives) $^{\bullet}$OH adducts formed under kinetic control can be distinguished from those formed under conditions of rapid equilibration.[26]

(iii) *Decarboxylation of 3-phenylpropanoic acid, its derivatives, and 4-phenylbutanoic acid.* Rapid decarboxylation of first-formed radical-cations is indicated by the detection of (3; $n = 1$) and (3; $n = 2$) from the reaction of $SO_4^{-\bullet}$ with $Ph(CH_2)_2CO_2^-$ and $Ph(CH_2)_3CO_2^-$, respectively. Since hydrated radicals are not detected we can assume that in both cases the rate constant for overall electron-transfer from side-chain to ring (and fragmentation) is $\geqslant 10^9$ s^{-1} (see earlier): as judged by the relative intensity of the signals from the two substrates we also conclude that reaction of the former is faster. On the other hand the results at low pH with $SO_4^{-\bullet}$ (and $^{\bullet}$OH) indicate either that loss of CO_2 from the corresponding acids is slower than loss of α-H or that cyclization is readily reversible (see Scheme 1). Our simple kinetic model is based on the assumption that the former is appropriate.

We suggest that the low-pH behaviour is governed, as for

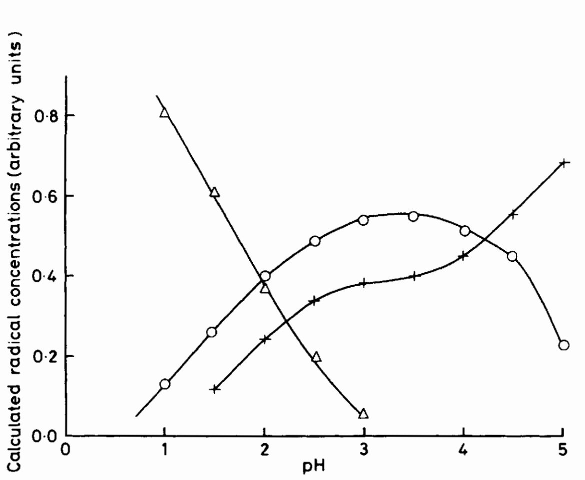


Figure 3. Simulated dependence on pH of the relative concentration of (3; n = 1) (○), (2; n = 1) (△), and the sum of hydroxycyclohexadienyl adducts (+) formed in the reaction of $^{\bullet}$OH and 3-phenylpropanoic acid. Rate constants were employed as follows (see Scheme 4): k_1 10^9 dm^3 mol^{-1} s^{-1}, k_2 10^9 dm^3 mol^{-1} s^{-1}, k_{-2} 2×10^7 dm^3 mol^{-1} s^{-1}, k_3 10^9 s^{-1}, $k_{3'}$ 10^6 s^{-1}, k_4, $k_{4'}$ 8×10^5 s^{-1} k_{-4}, $k_{-4'}$ 4×10^{10} dm^3 mol^{-1} s^{-1}, and all radical termination rate constants 10^9 dm^3 mol^{-1} s^{-1}

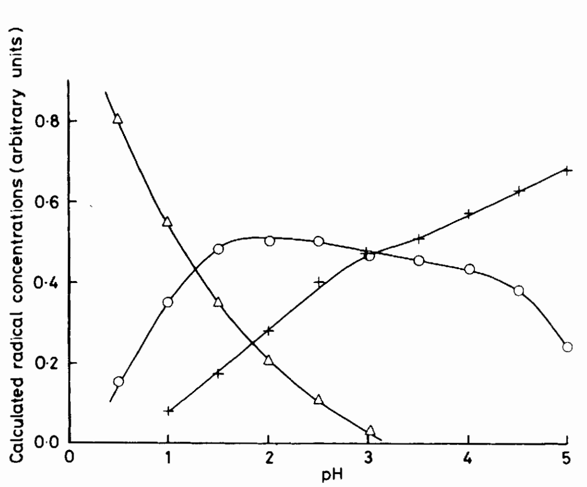
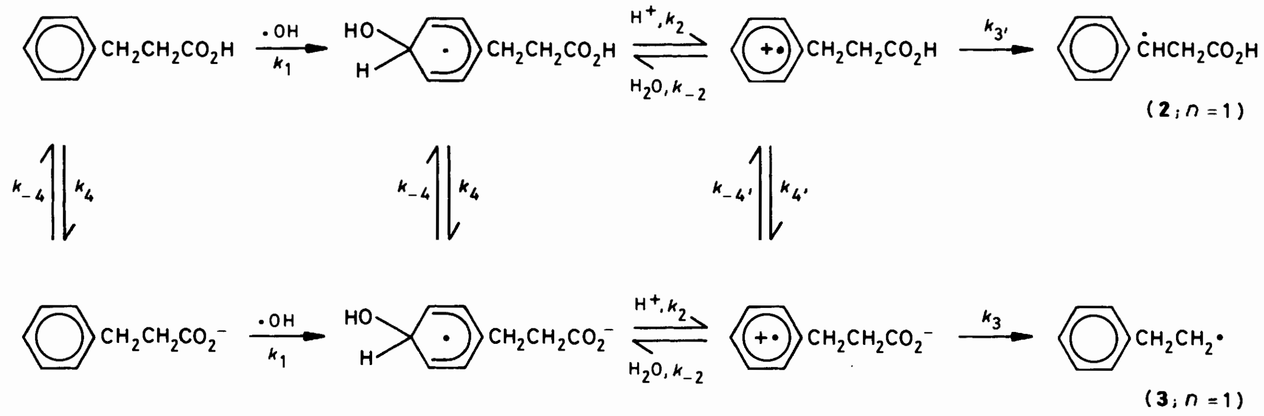


Figure 4. Simulated dependence on pH of the concentration of radicals derived from 3-phenylpropanoic acid and $^{\bullet}$OH (see Scheme 4 and Figure 3) but with k_2 5×10^8 dm^3 mol^{-1} s^{-1}, k_3 2×10^9 s^{-1}, and $k_{4'}$ 2×10^6 s^{-1}



Scheme 4.

methylbenzene and its derivatives, by the balance between deprotonation and rehydration (*cf.* methylbenzene itself) as well as the rate of acid-catalysed formation from cyclohexadienyl adducts (*cf.* phenylethanoic acid). The build-up of *e.g.* [PhCH$_2$CH$_2^{\bullet}$] as the pH is lowered in experiments with $^{\bullet}$OH and 3-phenylpropanoic acid (Figure 2) is believed to reflect the increased rate of acid-catalysed loss of OH$^-$ to give the radical-zwitterion (*i.e.* the cation-radical of the *anion*) and the subsequent disappearance is believed to reflect the increasing protonation of the carboxylate group in the intermediate and precursor. The balance of these two factors, which is expected to govern the high-pH 'cross-over' (as well as affect the onset of low-pH behaviour) was explored *via* kinetic simulation (see Scheme 4).

We initially employed $k_{3'}$ 10^6 s^{-1}, k_{-2} 2×10^7 dm^3 mol^{-1} s^{-1}, and k_2 10^9 dm^3 mol^{-1} s^{-1} (as for methylbenzene) with k_1 also 10^9 dm^3 mol^{-1} s^{-1} (as expected for attack on a typical aromatic substance); values of $2k_t$ for self- and cross-termination of adducts and product radicals were taken as 10^9 dm^3 mol^{-1} s^{-1}. The rate of decarboxylation (k_3) of the radical-zwitterion was initially taken as 10^9 s^{-1} and, in the first instance, the value of pK_a for each of the indicated acid–base equilibria was taken as 4.7, identical with that of the acid [*i.e.* on the initial assumption, possibly an oversimplification, that ionization of the acid is unaffected by formation of an adduct or cation-radical in the ring (k_{-4} was taken as 4×10^{10} dm^3 mol^{-1} s^{-1},[27] and k_4 calculated accordingly)].

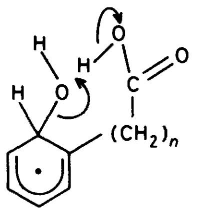
The calculated behaviour (see Figure 3) shows a reasonable resemblance to the experimental observations (as well as giving [R$^{\bullet}$] *ca.* 4×10^{-6} mol dm^{-3}, as observed), and the main features are clearly accounted for, though both 'intersections' occur at too high a pH and the predicted concentration of hydroxyl adducts appears to be somewhat too high. We therefore explored the variation of selected rate constants and particularly the effect on the two 'intersections' of the calculated curves.

For example with (4; n = 1), when the rate of acid-catalysed loss of water (k_2) is reduced to 5×10^8 dm^3 mol^{-1} s^{-1}, both (3; n = 1) and (2; n = 1) are effectively formed at somewhat lower pH values, as required, but the concentration of adducts in the pH range 2—4 is increased. Increase of the rate of decarboxylation (k_3) has a significant effect on the pH values at which both (3; n = 1) and (2; n = 1) are formed, increasing the range of pH over which PhCH$_2$CH$_2^{\bullet}$ is detected (but most markedly raising the high-pH intersection; for example a value of 5×10^{10} s^{-1} gives a high-pH 'intersection' at pH *ca.* 5, much greater than that observed). A combination of a small decrease in k_2 (*e.g.* to 5×10^8 dm^3 mol^{-1} s^{-1}) and a small increase in k_3 (to 2×10^9 s^{-1}) compared with the initial calculations (Figure 3) produces intersections for (2; n = 1) and (3; n = 1) at pH 1.7 and 2.8, though again leaving too high a proportion of hydroxyl adduct. We also explored the variation of k_3, the rate of deprotonation, and k_{-2}, the rate of rehydration of the radical-cations: the intersection of (**2**; $n = 1$) is, as would be expected, critically dependent on their ratio [for example a modest increase in $k_{3'}$ to $2 \times 10^{6}\ \mathrm{s^{-1}}$ gives an intersection for the generation of (**2**; $n = 1$) at pH 2.4, much higher than observed] and reduction in k_{-2} (*e.g.* to $10^{7}\ \mathrm{dm^{3}\ mol^{-1}\ s^{-1}}$) leads to the formation of (**3**; $n = 1$) as well as (**2**; $n = 1$) at pH values which are too high compared with experiment.

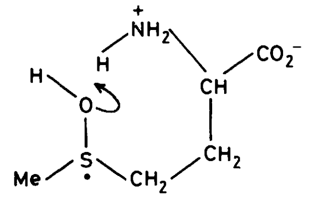
We also explored the effect of a small reduction of pK_a for the radical-cation and found a small but signficant improvement in the simulations (by widening slightly the gap between the two intersections and generally lowering the level of hydroxyl adducts in the middle of the pH range explored[*]). Figure 4 shows a set of calculations with pK_a 4.3, together with k_{-2} $2 \times 10^{7}\ \mathrm{dm^{3}\ mol^{-1}\ s^{-1}}$, k_3 $2 \times 10^{9}\ \mathrm{dm^{3}\ mol^{-1}\ s^{-1}}$, $k_{3'}$ $10^{6}\ \mathrm{s^{-1}}$, and k_2 $5 \times 10^{8}\ \mathrm{s^{-1}}$.

The number of variables clearly implies that confidence should not be placed in the individual values of the rate constants for the many processes involved in what is a complex overall mechanism. However, the nature of the results lend support to our interpretation of both $^{\bullet}OH$ and $SO_4^{-\bullet}$ results in terms of a mechanism in which at low pH the observation of deprotonation reflects a balance between formation (*via* OH loss), rehydration, and deprotonation of a radical-cation $^{+\bullet}ArCH_2CH_2CO_2H$ (*cf.* the reaction of methylbenzene) whereas the high pH behaviour reflects the decarboxylation (probably *via* direct electron-transfer) of the corresponding zwitterion. The latter reaction is evidently so rapid that rehydration is effectively prevented.

It is also possible that, in the reactions with $^{\bullet}OH$, formation of the radical-zwitterion is assisted by internal proton transfer from the carboxy group [once protonated, see (**27**)]; this would be closely analogous to the intramolecular catalysis for the loss of hydroxy proposed[28] for the methionine-OH adduct (**28**), a reaction which leads to the generation of a radical-cation (with, in close analogy to results described here, subsequent ring opening and decarboxylation). The ease of ring-opening of (**19**), compared with (**18**), to give (**23**), as the pH is lowered also suggests that hydroxyl adducts of the former may well give the radical-cation (**22**) *via* such intramolecular catalysis as shown for (**27**), a phenomenon which cannot be ruled out for adducts of other acids.



(**27**)



(**28**)

While it is possible that such catalysis could explain the behaviour of hydroxyl adducts of the acid forms in undergoing apparently more ready formation of the radical cation than, *e.g.*, the methylbenzene derivatives studied, we reiterate that the rapid decarboxylation of the cation-radicals of the anions (formed with $SO_4^{-\bullet}$ at high pH) can only be explained in terms of overall one-electron transfer.

Experimental

E.s.r. spectra were recorded with a Varian E-104 spectrometer equipped with 100 kHz modulation and an X-band klystron. Splitting constants were measured to within ± 0.005 mT and g factors to within ± 0.0001 by comparison with an aqueous solution of Fremy's salt [a(N) 1.3091 mT,[29] g 2.0055].[30] Relative radical concentrations were determined from measurements of peak heights (where the appropriate line-widths were the same) or by spectrum simulation (using a program kindly supplied by Dr. M. F. Chiu). Absolute radical concentrations were checked in some cases by comparison (using a Datalab DL4000 microcomputer) of the doubly integrated first-derivative signals with those obtained under identical conditions from $^{\bullet}CH_2OH$ (itself compared with a standard solution of vanadyl sulphate).

The rapid-flow experiments with redox couples were conducted using a Watson–Marlow 502S flow-inducer positioned on the inlet tubing of a mixing chamber which allowed the simultaneous mixing of three reactant streams before passage through the cavity of the spectrometer. The compositions of the solution to be mixed in experiments with $SO_4^{-\bullet}$ were typically as follows: stream (i) contained titanium(III) chloride (0.008 mol dm^{-3}), stream (ii) contained sodium peroxydisulphate (0.025 mol dm^{-3}), and the third stream contained the required substrate. For reactions above pH 2.5, EDTA (3 g dm^{-3}) was added to stream (i) together with sufficient ammonia solution (*d* 0.880) to give the required pH. For experiments at pH <2.5, the desired amount of concentrated sulphuric acid was added to steam (i). Experiments using $^{\bullet}OH$ were carried out using a similar system except that stream (ii) contained hydrogen peroxide (0.01 mol dm^{-3}).

The flow photolysis experiments were carried out using a typical flattened aqueous single cell with a built-in two-way mixer through which the solutions were forced by gravity (flow rate 2 cm^3 min^{-1}). The cell was irradiated in the cavity of the spectrometer using the unfiltered output of a Hanovia 977B-1 1 kW mercury–xenon compact arc. The two streams typically contained $Na_2S_2O_8$ (either 0.1 or 0.05 mol dm^{-3} with 0.3 mol dm^{-3} acetone) and the substrate (0.005—0.1 mol dm^{-3}), respectively. pH Adjustment was made using either ammonia solution (*d* 0.880) or concentrated sulphuric acid.

pH Measurements in both the flow and photolysis experiments were made using a Pye–Unicam PW9410 pH meter with the electrode inserted into the effluent stream. All solutions were degassed before use by purging with oxygen-free nitrogen.

Kinetic simulations were carried out using a program devised by Dr. A. Prothero (Shell Research Ltd), modified by Dr. T. M. F. Salmon and kindly provided by Professor D. J. Waddington.

The chemicals employed were commercial samples (and used as supplied) except for 2,3-dihydro-1*H*-indene-2-carboxylic acid[31] and *E*- and *Z*-2-phenylcyclopropanecarboxylic acids[32] which were prepared by standard procedures.

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[*] Such a direction of change of pK_a for the radical cation might be anticipated in view of the expected overall $-I$ effect created by the positive charge on the ring.

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