Electron Spin Resonance Studies. Part XLV.[1] Reactions of the Methyl Radical with Some Aliphatic Compounds in Aqueous Solution

By **Bruce C. Gilbert, Richard O. C. Norman,* Giuseppe Placucci, and Roger C. Sealy,** Department of Chemistry, The University of York, Heslington, York YO1 5DD

Results are reported of an e.s.r. investigation of the reactions of the methyl radical, generated from dimethyl sulphoxide with the Ti^{III}–H_2O_2 couple, with a variety of aliphatic compounds in aqueous solution. For example, with carboxylic acids and nitriles, the spectra of radicals formed by hydrogen-atom abstraction are detected; it is shown that the methyl radical is more selective than hydroxy, having a relatively greater propensity for abstracting hydrogen from the carbon atom adjacent to the functional group, and rate constants for these reactions, which are in the range *ca.* 10^2—10^4 l mol^{-1} s^{-1}, have been determined. Reaction with nitromethane is more complex. The spectra observed are those of the nitroethane radical-anion or its conjugate acid, depending on the pH, and it is concluded that abstraction by the methyl radical to give $\cdot CH_2NO_2$ is followed by rapid one-electron reduction by Ti^{III} to give the *aci*-compound to which methyl then adds. Nitroethane behaves analogously, and both $EtNO_2H$ and Pr^iNO_2H radicals are estimated to have pK_a 4·4.

THE reactions of the methyl radical in the gas phase have been studied extensively[2] but comparatively little is known of their reactions in aqueous solution. Thus, under the latter conditions, a small number of rate constants has been estimated from steady-state radiolysis experiments[3] and addition of the methyl radical to activated olefins has been studied by e.s.r. spectroscopy.[4]

We have recently shown that the reactions of the hydroxyl radical with aliphatic sulphoxides are excellent methods for the generation of specific (substituted) alkyl

---

[1] Part XLIV, B. C. Gilbert, R. O. C. Norman, and R. C. Sealy, *J.C.S. Perkin II*, 1975, 308.

[2] *E.g.*, P. Gray, A. A. Herod, and A. Jones, *Chem. Rev.*, 1971, **71**, 247.

[3] J. K. Thomas, *J. Phys. Chem.*, 1967, **71**, 1919.

[4] H. Fischer, *Adv. Polymer Sci.*, 1968, **5**, 463.

radicals for e.s.r. study.[1,5] We have now developed this approach for studying the reactions of the methyl radical with a range of aliphatic compounds; in particular, we have been able to obtain information about the selectivity of the radical in abstracting a hydrogen atom from two positions within a compound and the absolute rate constants for several reactions. The results enable comparisons to be made with the behaviour of the hydroxyl radical.

RESULTS AND DISCUSSION

The methyl radical was generated in a flow system by the reaction of dimethyl sulphoxide with the titanium(III)-hydrogen peroxide couple, usually at pH *ca.* 1. We have shown previously that the hydroxyl radical, formed by reaction (1), is converted essentially quantitatively into the methyl radical [reaction (2)] and that,

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

$$\mathrm{{\cdot}OH + Me_2SO \longrightarrow Me{\cdot} + MeSO_2H} \qquad (2)$$

provided the rate of radical initiation is fairly low, none of the secondary radical, $MeSO_2\cdot$, is detected from oxidation of methanesulphinic acid.[5]

In order to study the reactions of the methyl radical generated in this way with an added organic compound, it is necessary to employ conditions such that essentially all hydroxyl radicals are scavenged by dimethyl sulphoxide; otherwise, radicals from the added compound which are monitored by e.s.r. spectroscopy may owe their formation to attack by the hydroxyl rather than the methyl radical. Fortunately, the rate constant for the reaction of the hydroxyl radical with dimethyl sulphoxide is close to the diffusion-controlled limit,[6] and significantly greater than those for the reactions with the aliphatic compounds which we wished to study. In addition, except where stated, we employed a much higher concentration of the sulphoxide than of the second organic compound. Nevertheless, conditions could not always be adjusted to ensure that a radical observed from an added compound was formed essentially only by the reaction of the methyl radical with that compound; the checks made to determine whether the necessary condition was fulfilled, and the limitations of the method in certain instances, are described in the sequel.

Abstraction of Hydrogen from C–H *Bonds.*—The radicals detected by e.s.r. spectroscopy during oxidation with (a) the titanium(III)-peroxide couple (*i.e.* oxidation by $\cdot OH$) and (b) this couple in the presence of dimethyl sulphoxide (*i.e.* oxidation by $Me\cdot$ and/or $\cdot OH$; see later) are shown in Table 1; under the latter conditions, the methyl radical was always present in higher concentration than any other radical. The following radicals were identified by their hyperfine splitting constants: $Me\cdot$, $\cdot CH_2CO_2H$,[7] $\cdot CH_2CH_2CO_2H$,[8] $\cdot CHMeCO_2H$,[7] $\cdot CH_2CHMeCO_2H$, $\cdot CMe_2CO_2H$,[9] $\cdot CH(OH)CO_2H$, $\cdot CMe(OH)CO_2H$,[8] $\cdot CH(CN)CO_2H$, $\cdot CHMeCN$, $\cdot CMe_2CN$,[10] $\cdot CH_2CH_2COEt$,[11] $\cdot CHMeCOEt$,[12] $\cdot CH_2CH_2CO_2Me$,

TABLE 1

Radicals, and their hyperfine splitting constants, detected during oxidation with (a) the titanium(III)-peroxide couple, and (b) this couple in the presence of dimethyl sulphoxide

RH	Conditions	R·	Hyperfine splittings/mT
$MeCO_2H$	a, b	$Me\cdot$	2·29 (3H)
	a, b	$\cdot CH_2CO_2H$	2·14 (2H)
$EtCO_2H$	a, b	$\cdot CH_2CH_2CO_2H$	2·24 (2H), 2·65 (2H)
	a, b	$\cdot CHMeCO_2H$	2·02 (1H), 2·49 (3H)
Pr^iCO_2H	a	$\cdot CH_2CHMeCO_2H$	2·23 (2H), 2·58 (1H)
	a, b	$\cdot CMe_2CO_2H$	2·16 (6H)
CH_2ClCO_2H	a, b	$\cdot CH^{37}ClCO_2H$	2·00 (1H), 0·307 ($1^{37}Cl$)
		$\cdot CH^{35}ClCO_2H$	2·01 (1H), 0·370 ($1^{35}Cl$)
$CH_2(OH)CO_2H$	a, b	$\cdot CH(OH)CO_2H$	1·70 (1H), 0·26 (1H)
$MeCH(OH)CO_2H$	a, b	$\cdot CMe(OH)CO_2H$	1·68 (3H), 0·19 (1H)
	a	$\cdot CH_2CH(OH)CO_2H$	2·23 (2H), 2·67 (1H)
$CH_2(CN)CO_2H$	b	$\cdot CH(CN)CO_2H$	1·98 (1H), 0·31 (1N)
$EtCN$	a	$\cdot CH_2CH_2CN$	2·28 (2H), 2·68 (2H)
	a, b	$\cdot CHMeCN$	2·03 (1H), 2·30 (3H), 0·35 (1N)
Pr^iCN	a	$\cdot CH_2CHMeCN$	2·24 (2H), 2·44 (1H)
	a, b	$\cdot CMe_2CN$	2·07 (6H), 0·34 (1N)
$CH_2(OH)CH_2CN$	a, b	$\cdot CH(OH)CH_2CN$	1·52 (1H), 1·69 (2H)
	a	$\cdot CH(CH_2OH)CN$ *	
Et_2CO	a	$\cdot CH_2CH_2COEt$	2·21 (2H), 2·48 (2H)
	a, b	$\cdot CHMeCOEt$	1·86 (1H), 2·25 (3H), 0·27 (2H)
$EtCO_2Me$	a	$\cdot CH_2CH_2CO_2Me$	2·23 (2H), 2·70 (2H)
	a, b	$\cdot CHMeCO_2Me$	2·03 (1H), 2·43 (3H), 0·16 (3H)
$MeCO_2Et$	a	$\cdot CH_2CH_2OAc$	2·20 (2H), 2·51 (2H)
	a, b	$\cdot CHMeOAc$	1·89 (1H), 2·41 (3H), 0·15 (3H)

* Weak signals; see text.

---

[5] B. C. Gilbert, R. O. C. Norman, and R. C. Sealy, *J.C.S. Perkin II*, 1975, 303.

[6] G. Meissner, A. Henglein, and G. Beck, *Z. Naturforsch.*, 1967, **22b**, 13.

[7] A. L. J. Beckwith and R. O. C. Norman, *J. Chem. Soc.* (*B*), 1969, 400.

[8] W. T. Dixon, R. O. C. Norman, and A. L. Buley, *J. Chem. Soc.*, 1964, 3625.

[9] P. Smith, J. T. Pearson, P. B. Wood, and T. C. Smith, *J. Chem. Phys.*, 1965, **43**, 1535.

[10] R. Livingston and H. Zeldes, *J. Magnetic Resonance*, 1969, **1**, 169.

[11] B. C. Gilbert, R. O. C. Norman, and R. C. Sealy, *J.C.S. Perkin II*, 1973, 2174.

[12] H. Fischer, *Z. Naturforsch.*, 1965, **20a**, 428.

$\cdot CHMeCO_2Me$, $\cdot CH_2CH_2OAc$, $\cdot CHMeOAc$.[9] Assignments of previously unreported spectra are straightforward: for example, the spectrum from propiononitrile with $a(2H)$ 2·28, $a(2H)$ 2·68 mT is assigned to $\cdot CH_2CH_2CN$, with splittings from the α- and β-protons, respectively; that from isobutyronitrile with $a(2H)$ 2·24, $a(1H)$ 2·44 mT is assigned to $\cdot CH_2CHMeCN$; and the spectrum from 3-hydroxypropiononitrile [$a(1H)$ 1·52, $a(2H)$ 1·69 mT] ascribed to $\cdot CH(OH)CH_2CN$. Both chlorine-35 and -37 splittings were resolved in the spectrum from chloroacetic acid; $a(^{37}Cl) : a(^{35}Cl)$ and $[\cdot CH^{35}ClCO_2H] : [\cdot CH^{37}ClCO_2H]$ ratios of 0·83 and *ca.* 3 respectively are in good agreement with predicted values from the magnetic moments (0·832[13]) and abundances (3·07). In addition to the spectra described in Table 1, additional weak lines were obtained from 3-hydroxypropiononitrile which are probably the spectrum of $\cdot CH(CH_2OH)CN$. No spectrum could be detected from acetonitrile. For those compounds which undergo hydrogen-atom abstraction from each of two positions, the relative concentrations of the resulting two radicals are shown in Table 2.

TABLE 2

Relative concentrations of radicals detected by e.s.r. spectroscopy from oxidation of compounds which yield two radicals by hydrogen-atom abstraction with (a) the titanium(III)–peroxide couple, and (b) this couple in the presence of dimethyl sulphoxide

	Relative concentrations $[A]/[B]$ [a]	
Compound	a	b
$EtCO_2H$	1·2	3·0
Pr^iCO_2H	1·05	$>4·0$ [b]
$MeCH(OH)CO_2H$	6·8	$>13·0$ [b]
EtCN	1·1	4·0
Pr^iCN	1·2	$>4·0$ [b]
Et_2CO	1·7	$>6·8$ [b]
$EtCO_2Me$	1·2	$>3·9$ [b]
EtOAc	1·4	$>2·1$ [b]

[a] Radicals *A* and *B* are those from abstraction of hydrogen from C–H bonds respectively adjacent to, and one carbon atom further removed from, the functional groups CO_2H, CN, COEt, CO_2Me, or OAc. [b] The radical *B* was not detected under these conditions.

For reactions initiated by the titanium(III)–peroxide couple under our conditions, short-lived radicals, *e.g.*, those which undergo bimolecular termination with a rate constant of the order of 10^9 l mol^{-1} s^{-1}, as those in Table 1 are expected to do, are observed at a steady-state concentration in the e.s.r. cavity.[14] Now, since reactions of this couple in the presence of dimethyl sulphoxide and another organic compound always gave observed concentrations of the methyl radical in significant excess of those of a radical, R·, from the latter compound, bimolecular termination for R· should be predominantly by reaction (4). Moreover, except in the specific case mentioned later, the radicals in Table 1 are not expected either to be oxidised by hydrogen peroxide[15] or to be reduced by titanium(III)[11] at a rate which will contribute materially to termination. Therefore, in those cases where the generation of R· *from* RH can be shown to be essentially entirely the result of reaction (3), the steady-state approximation yields equation (5). Since k_4 may be taken as $3·2 \times 10^9$ l mol^{-1} s^{-1} for small organic radicals R·,[5] an absolute radical concentration measurement enables k_3 to be evaluated. This is the basis of our kinetic analysis, the application of which is now discussed for individual compounds in more detail.

$$Me\cdot + RH \xrightarrow{k_3} MeH + R\cdot \qquad (3)$$

$$Me\cdot + R\cdot \xrightarrow{k_4} \text{molecular products} \qquad (4)$$

$$k_3 = k_4[R\cdot]/[RH] \qquad (5)$$

Carboxylic acids. The oxidation of M-acetic acid with the titanium(III)–peroxide couple in the presence of M-dimethyl sulphoxide gave the methyl and $\cdot CH_2CO_2H$ radicals in relative concentrations 14·5 : 1. Now, acetic acid reacts relatively slowly with the hydroxyl radical (*k ca.* 10^7 l mol^{-1} s^{-1}),[16,17] giving mainly[8] $\cdot CH_2CO_2H$ and some $\cdot CH_3$ as detected by e.s.r.; calculation, taking k_4 as $3·2 \times 10^9$ and $2k(Me\cdot + Me\cdot)$ as[5] $5·6 \times 10^9$ l mol^{-1} s^{-1}, together with the rate constants for ($\cdot OH + Me_2SO$) (7×10^9 l mol^{-1} s^{-1})[17] and ($\cdot OH + MeCO_2H$) and the relative concentrations of these compounds shows that, in the absence of reaction (6), the ratio $[Me\cdot] : [\cdot CH_2CO_2H]$ would be at least 400 : 1. We can infer * that the fraction of $\cdot CH_2CO_2H$ radicals which are formed by reaction of acetic acid with the methyl radical is (1 – 14·5/400), *i.e.* >95%, and application of equation (5) yields $k_6 = 2 \times 10^2$ l mol^{-1} s^{-1}.

$$Me\cdot + MeCO_2H \xrightarrow{k_6} MeH + \cdot CH_2CO_2H \qquad (6)$$

It should be noted that we would not have been able to detect a contribution from reaction (7) to the overall

$$MeCO_2H \xrightarrow{Me\cdot} MeCO_2\cdot \longrightarrow Me\cdot + CO_2 \qquad (7)$$

process. However, the homologous radicals were not detected from the other acids which were studied.

The reaction of propionic acid with the hydroxyl radical gave the radicals $\cdot CHMeCO_2H$ and $\cdot CH_2CH_2CO_2H$ in relative concentrations 1·2 : 1; providing that the rate coefficients for the three possible bimolecular termination reactions are similar,[18,19] the rates of formation of the two are in the same ratio. In contrast,

---

* Solution of the steady-state equations when $[Me\cdot] \gg [R\cdot]$ ($R = CH_2CO_2H$ in this case) gives $([R\cdot]/[Me\cdot])_{obs} = ([R\cdot]/[Me\cdot])_{OH} + ([R\cdot]/[Me\cdot])_{Me}$, where the subscripts OH and Me refer to the formation of R· from RH by reaction with the hydroxyl and methyl radicals, respectively. It follows that $[R\cdot]_{Me}/[R\cdot]_{obs} = 1 - ([Me\cdot]/[R\cdot])_{obs}/([Me\cdot]/[R\cdot])_{OH}$.

[13] 'Handbook of Chemistry and Physics,' The Chemical Rubber Co., Cleveland, 52nd edn., p. B-254.

[14] G. Czapski, *J. Phys. Chem.*, 1971, **75**, 2957; C. E. Burchill and P. W. Jones, *Canad. J. Chem.*, 1971, **49**, 4005.

[15] B. C. Gilbert, R. O. C. Norman, and R. C. Sealy, *J.C.S. Perkin II*, 1974, 824.

[16] J. K. Thomas, *Trans. Faraday Soc.*, 1965, **61**, 702.

[17] L. M. Dorfman and G. E. Adams, 'Reactivity of the Hydroxyl Radical in Aqueous Solution,' Report No. NSRDS-NBS-46, U.S. Government Printing Office, Washington, 1973.

[18] D. Meisel, G. Czapski, and A. Samuni, *J.C.S. Perkin II*, 1973, 1702.

[19] W. A. Pryor, 'Free Radicals,' McGraw-Hill, New York, 1966, p. 15.

when dimethyl sulphoxide was included, the observed ratio of concentrations was 3 : 1. Now, the ratios [Me•] : [•CHMeCO$_2$H] and [Me•] : [•CH$_2$CH$_2$CO$_2$H] under the latter conditions were 4·5 and 13·5 as compared with values of 20 and 25, respectively, which would be expected if the carboxy-containing radicals were formed only by hydroxyl-radical abstraction; we can infer that >75% of the observed •CHMeCO$_2$H radicals are formed by reaction (8), but cannot be sure that the majority of the radicals •CH$_2$CH$_2$CO$_2$H are formed analogously. Further, the former radicals might be generated in part from the latter as in reaction (9), although, since substituted alkyl radicals appear to be somewhat less reactive than methyl in hydrogen-atom abstraction,[2] any effect of this reaction should be small. Thus, from the absolute concentration of •CHMeCO$_2$H and equation (5), we estimate k_8 as $3{\cdot}0 \times 10^3$ l mol^{-1} s^{-1}. Given that the radical •CH$_2$CH$_2$CO$_2$H may be formed in significant measure by hydroxyl-radical abstraction, it follows that the rate constant for its formation by methyl-radical abstraction cannot be greater than 1×10^3 l mol^{-1} s^{-1} and is presumably less, so that the methyl radical is significantly more selective than hydroxyl towards propionic acid.

$$\mathrm{EtCO_2H} \xrightarrow{\mathrm{Me\cdot}} \mathrm{\cdot CHMeCO_2H} \qquad (8)$$

$$\mathrm{\cdot CH_2CH_2CO_2H + EtCO_2H} \longrightarrow \mathrm{EtCO_2H + \cdot CHMeCO_2H} \qquad (9)$$

Whereas isobutyric acid gave both •CMe$_2$CO$_2$H and •CH$_2$CHMeCO$_2$H with the hydroxyl radical, in relative concentrations 1·05 : 1, only the former was detected when dimethyl sulphoxide was included; analogous behaviour was observed with lactic acid (Table 2). For both •CMe$_2$CO$_2$H and •CMe(OH)CO$_2$H and for the radicals from chloro-, hydroxy-, and cyano-acetic acid, the relative concentrations of the methyl and the acid-derived radical, as compared with the values to be expected if abstraction from the carboxylic acid were by •OH, showed that the latter reaction was of little importance (<10%) as compared with methyl-radical abstraction; measurements of absolute radical concentrations and application of equation (5) gave the rate constants for the latter abstractions in Table 3. However, in the case of cyanoacetic acid the value given is a minimum since analogy with the ready reduction of[20] •CH(CO$_2$H)$_2$ by Ti$^{\mathrm{III}}$ suggests that reduction of •CH(CN)-CO$_2$H may contribute significantly to radical termination.

Nitriles. No radical could be detected during the oxidation of M-acetonitrile in the presence of dimethyl sulphoxide, indicating a maximum rate for hydrogen-atom abstraction by methyl of 3×10^2 l mol^{-1} s^{-1}.

The oxidation of propiononitrile with the hydroxyl radical gave both •CHMeCN and •CH$_2$CH$_2$CN, in relative concentrations 1·1 : 1. This is in contrast with the results reported for the photolysis of a mixture of the nitrile with hydrogen peroxide, which gave predominantly the former radical,[10] perhaps because of an effect of the difference in the media or possibly because, under the latter conditions, reaction (10) assumes importance. Reaction in the presence of dimethyl sulphoxide gave a substantially higher ratio; as with propionic acid, it was possible to show, from the relative concentrations of the radicals •CHMeCN and Me• as compared with expectation if the former resulted only from abstraction by hydroxyl, that reaction (11) predominated (>90%);* an absolute measurement of radical concentration gave $k_{11} = 1{\cdot}2 \times 10^3$ l mol^{-1} s^{-1}.

$$\mathrm{\cdot CH_2CH_2CN + EtCN} \longrightarrow \mathrm{EtCN + \cdot CHMeCN} \qquad (10)$$

$$\mathrm{EtCN} \xrightarrow{\mathrm{Me\cdot}} \mathrm{\cdot CHMeCN} \qquad (11)$$

Whereas there was evidence for the formation of both possible carbon radicals from isobutyronitrile and 3-hydroxypropiononitrile with hydroxyl, only one was detected in the presence of dimethyl sulphoxide. Analysis as described above † shows that, under the latter conditions, the radical from the former compound but not from the latter resulted mainly (>80%) from reaction of the nitrile with the methyl radical; the derived rate constants are in Table 3. The much higher observed concentration of •CH(OH)CH$_2$CN than of •CH(CH$_2$OH)CN from 3-hydroxypropiononitrile with hydroxyl is again in contrast with the results[10] of photolysis of nitrile–peroxide mixtures which gives mainly the latter radical.

Other compounds. The results obtained by oxidising diethyl ketone and methyl propionate in the presence of dimethyl sulphoxide were shown, by analysis similar to that described above, to reflect mainly (>90%) oxidation by the methyl rather than the hydroxyl radical. However, we could not establish this for the oxidation of ethyl acetate.

The results in Table 3 and described above enable the following conclusions to be drawn. First, rate constants for abstraction by the methyl radical are much lower than for the hydroxyl radical[17] and, correspondingly, methyl is the more selective of the two. Nonetheless, there is an indication that, as previously suggested,[3] methyl reacts faster in aqueous solution than in the gas phase at the same temperature; thus, although it can be dangerous to extrapolate high-temperature, gas-phase data, it is notable that the rate constant so

---

* This value is based on k(•OH + EtCN)[21] and the assumption that only hydrogen-atom abstraction occurs. However, it has been suggested that reaction occurs, at least in part, by addition to the nitrile function.[21] If so, then our figure of 90% is an underestimate.

† Rates of reaction with the hydroxyl radical are available only for acetonitrile[17] and propiononitrile[21] of the nitriles investigated. Estimates for other nitriles were therefore based on the assumption that they react at the same rate as the corresponding carboxylic acids. Since acetonitrile and propiononitrile are less reactive than acetic acid and propionic acid, respectively, towards •OH, this almost certainly overestimates the significance of hydroxyl-radical reactions, so that the values for the minimum proportion of reaction involving the methyl radical are likely to be even higher than those quoted.

[20] D. Behar, A. Samuni, and R. W. Fessenden, *J. Phys. Chem.*, 1973, **77**, 2055.

[21] I. Draganić, Z. Draganić, Lj. Petković, and A. Nikolić, *J. Amer. Chem. Soc.*, 1973, **95**, 7193.

obtained for abstraction of hydrogen from $MeCO_2D$ at 25°,[2] 6 l mol^{-1} s^{-1}, is only about one-thirtieth of that for reaction (6) at ambient temperature in aqueous solution (*cf.* the hydroxyl radical [22]).

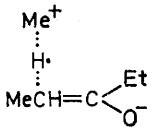
TABLE 3

Rate constants for hydrogen-atom abstraction by the methyl radical from the italicised CH group [a]

Compound	$10^{-3}k$/ l mol^{-1} s^{-1}	Compound	$10^{-3}k$/ l mol^{-1} s^{-1}
$\mathit{Me}CO_2H$	0·2	$\mathit{Me}CN$	<0·3
$Me\mathit{CH}_2CO_2H$	3·0	$Me\mathit{CH}_2CN$	1·2
$Me_2\mathit{CH}CO_2H$	9·0	$Me_2\mathit{CH}CN$	4·5
$Cl\mathit{CH}_2CO_2H$	3·0	$NCCH_2\mathit{CH}_2OH$	<1·6
$HO\mathit{CH}_2CO_2H$	3·6	$Me\mathit{CH}_2COEt$	14·0
$HO\mathit{CH}MeCO_2H$	12·0	$Me\mathit{CH}_2CO_2Me$	2·9
$NC\mathit{CH}_2CO_2H$	>6·6	$Me\mathit{CH}_2OAc$	<1·7

[a] Not corrected for statistical effects.

Secondly, the effectiveness of a substituent, X, in activating the adjacent methylene group to hydrogen-atom abstraction falls in the order, $X = COEt > CO_2H \sim CO_2Me > CN$. This is not the same as the order for the capacity of these substituents to delocalise the unpaired electron in the resulting radical [$COEt > CN > CO_2H > CO_2Me$, as estimated from a(Me) in the radicals $\cdot CHMeX$; *cf.* refs. 12 and 23], but it corresponds to the order $COMe > CO_2Et > CN$ for the mesomeric electron-accepting capacity of these substituents as measured by [24] σ_R. This is consistent with the importance of polar structures such as (1) in describing the transition state for hydrogen-atom abstraction, reflecting the nucleophilic character [25, 26] of the methyl radical.



(1)

Thirdly, the introduction of a methyl group for hydrogen at the carbon atom from which abstraction occurs is accompanied by a significant increase in rate; for example, for a single hydrogen atom, the ratios of rate constants for $MeCO_2H$, $EtCO_2H$, and Pr^iCO_2H are 1 : 22·5 : 135. The introduction of Cl or OH has a similar effect to methyl.

Reactions of Nitro-compounds.—When nitromethane was included in the titanium(III)–peroxide–dimethyl sulphoxide system, with $[Ti^{III}] > ca.\ 10^{-4}$M, only the methyl radical was detected. However, when $[Ti^{III}]$ was reduced, the spectrum of this radical was partially quenched by nitromethane and that of the radical-anion of nitro*ethane* [27, 28] or its conjugate acid,[29] depending on the pH (see later), appeared. Likewise, nitroethane gave the radical-anion of 2-nitropropane [27, 28] or its conjugate acid.[29] Our e.s.r. parameters (Table 4) are in good agreement with those reported for aqueous solution.[27–29]

TABLE 4

Radicals derived from nitroalkanes with the titanium(III)–hydrogen peroxide–dimethyl sulphoxide system

Nitroalkane	pH	Radical	Hyperfine splittings/ mT
$MeNO_2$	2	$Et\dot{N}O_2H$	2·81 (1N), 0·91 (2H), 0·32 (1H)
	6	$EtNO_2^{-\cdot}$	2·59 (1N), 0·97 (2H)
	2 *	$HOCH_2\dot{N}O_2H$	2·70 (1N), 0·67 (2H), 0·32 (1H)
$EtNO_2$	2	$Me_2CH{\cdot}\dot{N}O_2H$	2·82 (1N), 0·49 (1H), 0·36 (1H)
	6	$Me_2CH{\cdot}NO_2^{-\cdot}$	2·60 (1N), 0·46 (1H), 0·03 (6H)

* In the absence of dimethyl sulphoxide.

In the presence of nitromethane but the absence of dimethyl sulphoxide, we obtained a spectrum which we attribute to $HO{\cdot}CH_2{\cdot}\dot{N}O_2H$ on the basis of the magnitude of the nitrogen splitting and the single-proton splitting (*cf.* $Et\dot{N}O_2H$); that splitting from the methylene protons is smaller than in $Et\dot{N}O_2H$ is not exceptional, since its magnitude should be conformation dependent. At higher pH this spectrum was replaced by some very weak lines consistent with the spectrum of the corresponding radical anion.[30] No radicals were detected from nitroethane under either conditions.

The formation of the radicals in Table 4 from the compounds studied was unexpected. Moreover, both acid and base forms of these radicals are almost certainly highly transient (*cf.* data [31] for $Me\dot{N}O_2H$ and $MeNO_2^{-\cdot}$), so that their detection in significant amounts renders it unlikely that they result from minor side reactions.

We considered first the possibility that the species might be formed by addition of the methyl or hydroxyl radical to *aci*-tautomers of the nitro-compounds, or their anions (*cf.* ref. 28). However, the concentration of the *aci*-form derived from 0·8M-nitromethane is $<10^{-7}$M, and that of its anion at pH 2 is even lower; thus, even if the addition reactions were to occur at a rate approaching the diffusion-controlled limit, addition could not compete effectively with bimolecular termination for the removal of methyl from the system. An alternative possibility for reactions in the presence of dimethyl sulphoxide, which is consistent with our experimental results, is set out in the Scheme; individual steps are justified in the sequel.

Since the hydroxyl radical reacts much faster with dimethyl sulphoxide than with nitroalkanes ($k < 5 \times$

---

[22] C. Walling, G. M. El-Taliawi, and R. A. Johnson, *J. Amer. Chem. Soc.*, 1974, **96**, 133.

[23] H. Fischer, *Z. Naturforsch.*, 1964, **19a**, 866.

[24] J. March, 'Advanced Organic Chemistry: Reactions, Mechanisms, and Structure,' McGraw-Hill, New York, 1970, p. 243.

[25] R. O. C. Norman, *Chem. and Ind.*, 1973, 874.

[26] B. R. Cowley, R. O. C. Norman, and W. A. Waters, *J. Chem. Soc.*, 1959, 1799.

[27] L. H. Piette, P. Ludwig, and R. N. Adams, *J. Amer. Chem. Soc.*, 1962, **84**, 4212.

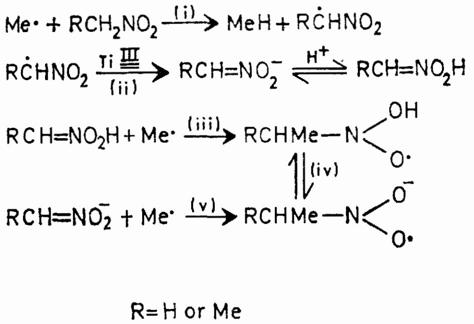
[28] M. McMillan and R. O. C. Norman, *J. Chem. Soc. (B)*, 1968, 590.

[29] D. J. Edge and R. O. C. Norman, *J. Chem. Soc. (B)*, 1970, 1083.

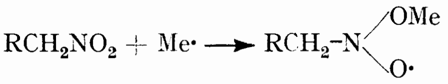
[30] K. Eiben and R. W. Fessenden, *J. Phys. Chem.*, 1968, **72**, 3387.

[31] K.-D. Asmus, A. Henglein, and G. Beck, *Ber. Bunsengesellschaft Phys. Chem.*, 1966, **70**, 459.

10^6 l mol^{-1} s^{-1} for nitromethane[31]), essentially all hydroxyl radicals are scavenged by the former under our conditions ([Me_2SO]/[RCH_2NO_2] *ca.* 0·15—0·30); the radicals formed in the presence of the sulphoxide therefore arise from reactions involving the methyl radical and the nitroalkane. Of the two ways in which this radical might react with a nitroalkane, one, addition at the nitro-group as in reaction (12), would be expected to give a species detectable by e.s.r. spectroscopy if it were to occur rapidly enough (*cf.* ref. 28), but species of this type were not observed with either of the nitroalkanes; further, no signals were detected from two aromatic nitro-compounds (10^{-2}M-5-nitrobenzene-1,3-dicarboxylic acid at pH 8 or 10^{-3}M-4-nitrophenol at pH 1). In contrast, the alternative reaction, step (i) in the Scheme, is thought to play an important role in the thermal decomposition of nitroalkanes[32] and its rate constant has been determined in the gas phase at 200° as[33] 1·6 × 10^4 l mol^{-1} s^{-1}. If we assume[33] an activation energy of *ca.* 9 kcal mol^{-1}, then extrapolation to ambient temperature gives a rate constant of *ca.* 10^2 l mol^{-1} s^{-1}. Given that the errors involved in such extrapolations are large, and that reaction in aqueous solution may be faster than in the gas phase, it is likely that the rate constant is large enough (*ca.* 10^3 l mol^{-1} s^{-1}) for step (i) to contribute significantly to the removal of the methyl radical from the system under conditions in which the rate of radical initiation is relatively low * and [RCH_2NO_2] is large; moreover, as was noted earlier, high rates of radical initiation in our experiments resulted in the detection of the methyl radical only.



SCHEME



$$RCH_2NO_2 + Me\cdot \longrightarrow RCH_2\text{-}N\begin{matrix}\diagup OMe\\ \diagdown O\cdot\end{matrix} \qquad (12)$$

We were unable to detect the radicals $\cdot CHR\cdot NO_2$ in our experiments, but this was not unexpected. We have previously obtained evidence that they are formed rapidly by the one-electron reduction of α-halogenonitroalkanes by donor radicals such as $\cdot CO_2H$ or by Ti^{III} ions complexed by tartaric acid but are not observed by e.s.r. spectroscopy because of their rapid reduction by Ti^{III} ions;[34] further, as judged by the greater acidity of nitro-methane or -ethane[35] than analogous aldehydes or ketones,[36] the nitro-group should facilitate the reduction in step (ii) more than a carbonyl group, so that it is not surprising that nitro-conjugated radicals are not detectable under reaction conditions in which the reduction of carbonyl-conjugated radicals does not contribute significantly to radical termination.[11]

The nitromethane *aci*-anion is an excellent trap for carbon-centred radicals in solution,[37] and similar properties might be expected for its conjugate acid, $CH_2{:}NO_2H$, and the analogous species from nitroethane. Thus, steps (iii) and (v) are reasonable, the relative importance of each depending on the pH ($RCH{:}NO_2H$ has pK_a *ca.* 3 and 4·5 for R = H and Me, respectively[35]) as well as the rate constants for the reactions. These steps must compete effectively with both the dimerisation of the methyl radical and step (i), and since the concentration of the *aci*-compound in the e.s.r. cavity can never be much greater than *ca.* 10^{-4}M,† we estimate the rate constants for steps (iii) and (v) as $>10^7$ l mol^{-1} s^{-1}.

In the absence of dimethyl sulphoxide, the formation of $HO\cdot CH_2\cdot NO_2^{-\cdot}$ and its conjugate acid presumably occurs as in the Scheme with ·OH in place of Me·. The detection of these nitro-containing radicals implies that the rate constants for addition of ·OH to $CH_2{:}NO_2H$ and its conjugate base are much greater (by a factor of at least 10^4) than that for reaction (13; R = H). Since the former cannot be greater than *ca.* 10^{10} l mol^{-1} s^{-1}, k_{13} (R = H) must be $<10^6$ l mol^{-1} s^{-1}, consistent with the results of Asmus *et al.* who were unable to detect any reaction between ·OH and $MeNO_2$ under their conditions (k $<5 \times 10^6$ l mol^{-1} s^{-1}).[31] Finally, the absence of detectable radicals from nitroethane under conditions in which nitromethane yields $HO\cdot CH_2\cdot NO_2^{-\cdot}$ and its conjugate acid would follow if, as we should expect from the data in Table 3, reaction (13) were significantly faster for R = Me compared with R = H, so that essentially all hydroxyl radicals are scavenged by the nitroethane.

$$RCH_2NO_2 + \cdot OH \longrightarrow R\dot{C}HNO_2 + H_2O \qquad (13)$$

pK_a *of* $RCHMe\cdot\dot{N}O_2H$.—The observed relative concentrations of the radical $RCHMe\cdot\dot{N}O_2H$ (R = H or Me) and its conjugate base would be those corresponding to equilibrium conditions for reaction (14) if the forward and reverse steps of that reaction were to occur rapidly relative to radical termination. Now, assuming that bimolecular termination occurs at about the same rate

---

* Detection of the radicals in Table 4 was achieved with rates of initiation which gave [Me·]$_{s.s.}$ $< 5 \times 10^{-7}$M in the absence of the nitroalkane.

† This concentration is maximal for k(i)[RCH_2NO_2] = k(iii)[$RCH{:}NO_2H$] + k(v)[$RCH{:}NO_2^-$], provided that the system is governed by quasi-steady-state kinetics.

[32] P. Gray, A. D. Ioffe, and L. Roselaar, *Trans. Faraday Soc.*, 1955, **51**, 1489.

[33] T. V. Fedorova, A. P. Ballol, and V. Ya. Shtern, *Kinetika i Kataliz*, 1970, **11**, 1052.

[34] N. H. Anderson, M. McMillan, and R. O. C. Norman, *J. Chem. Soc.* (*B*), 1970, 1075.

[35] D. Turnbull and S. H. Maron, *J. Amer. Chem. Soc.*, 1943, **65**, 212.

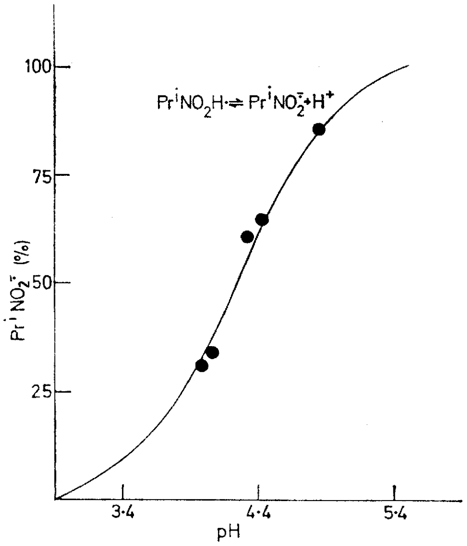
[36] R. G. Pearson and R. L. Dillon, *J. Amer. Chem. Soc.*, 1953, **75**, 2439.

[37] B. C. Gilbert, J. P. Larkin, and R. O. C. Norman, *J.C.S. Perkin II*, 1972, 1272.

as for $\mathrm{Me\dot{N}O_2H}$,[31] then, since $[\mathrm{RCHMe{\cdot}\dot{N}O_2H}] + [\mathrm{RCHMe{\cdot}NO_2^{-\cdot}}]$ was $<10^{-6}$M, the conditions for the establishment of equilibrium (14) are that k_{14} and $k_{-14}[\mathrm{H^+}]$ should be $\gg 5 \times 10^2\ \mathrm{s^{-1}}$. This should be so, for rate constants for protonation on oxygen are generally[38] $>10^{10}$ l mol^{-1} s^{-1} and preliminary experiments indicated that the pK_a values were in the range 4—5; thus, in the pH range 3·5—5·5, $k_{-14}[\mathrm{H^+}]$ should be $>3 \times 10^4\ \mathrm{s^{-1}}$ and k_{14} is probably 10^5—10^6 s^{-1}. We are therefore able to obtain pK_a values by monitoring the relative concentrations of the radicals in equation (14) at a suitable pH.

$$\mathrm{RCHMe{\cdot}\dot{N}O_2H} \rightleftharpoons \mathrm{RCHMe{\cdot}NO_2^{-\cdot}} + \mathrm{H^+} \qquad (14)$$

In initial experiments we were unable to obtain reproducible pK_a values when the pH was adjusted with ammonia and measured on exit from the e.s.r. cavity. Tests indicated that this was probably owing to removal of titanium(III) ion and concomitant generation of hydroxide ion along the flow-tube, so that the pH on exit was somewhat higher than that in the cavity. We therefore buffered solutions to the desired pH with citric acid and disodium hydrogen orthophosphate which, apart from stabilising the pH, have the advantage that their components are of low reactivity towards the hydroxyl radical.[17,39] The results obtained in this way for $\mathrm{Me_2CH{\cdot}\dot{N}O_2H}$ are shown in the Figure; the experimental points are in good agreement with the theoretical curve for pK_a 4·4. A similar good fit was obtained for $\mathrm{Et\dot{N}O_2H}$ with pK_a again 4·4. These values are the same as that obtained for $\mathrm{Me\dot{N}O_2H}$ by a pulse-radiolysis study.[31]



Variation with pH of $[\mathrm{Pr^iNO_2^{-\cdot}}]$ expressed as a percentage of the sum of $[\mathrm{Pr^iNO_2^{-\cdot}}] + [\mathrm{Pr^iNO_2H}]$; the continuous curve is that expected for an acid of pK_a 4·4

EXPERIMENTAL

The e.s.r. spectrometer and flow system have been described in detail.[11] Splitting constants were measured both directly and by comparison with Fremy's salt [a(N) 1·3091 mT [40]]. Ratios of radical concentrations were obtained from measurements of peak amplitude and linewidth, and absolute radical concentrations were measured by comparison with a standard solution of Fremy's salt.

A three-stream mixing chamber was employed in all experiments. For reactions at *ca.* pH 1 the three streams contained (i) titanium(III) chloride (5mM) together with sulphuric acid solution (10 ml l^{-1}); (ii) hydrogen peroxide (24mM); and (iii) dimethyl sulphoxide (0·3—3M) and/or another organic substrate (0·15—3M). For experiments at pH above *ca.* 2·5, either stream (i) contained titanium(III) chloride as above together with EDTA (5mM) and sufficient ammonia to attain the required pH, or the titanium(III)–EDTA complex was made up in a citric acid–disodium hydrogen orthophosphate buffer [41] (pH 3·5—5·5). Streams (ii) and (iii) were as above. pH Measurements were made to within ±0·1 pH units with an Electronic Instruments model 23A pH meter.

Chemicals used were commercial samples. Titanium(III) chloride, hydrogen peroxide (100 volume), EDTA (disodium salt), disodium hydrogen orthophosphate, ammonia solution (*d* 0·88), sulphuric acid, acetic acid, chloroacetic acid, propionic acid, glycolic acid, lactic acid, isobutyric acid, dimethyl sulphoxide, nitromethane, and nitroethane were from Fisons Limited, acetonitrile, propiononitrile, isobutyronitrile, and 3-hydroxypropiononitrile from Koch–Light Laboratories, and cyanoacetic acid, methyl propionate, and ethyl acetate from B.D.H.

The award of an I.C.I. Fellowship (to R. C. S.) is gratefully acknowledged.

[4/2354 *Received*, 11*th November*, 1974]

---

[38] M. Eigen, *Angew. Chem. Internat. Edn.*, 1964, **3**, 1.

[39] G. Grabner, N. Getoff, and F. Schwoerer, *Internat. J. Radiation Phys. Chem.*, 1973, **5**, 393, 405.

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

[41] 'Data for Biochemical Research,' eds. R. M. C. Dawson, D. C. Elliott, W. H. Elliott, and K. M. Jones, Oxford University Press, Oxford, 1969.