Trapping of Short-Lived Free Radicals as Nitroxide Radicals Detectable by ESR Spectroscopy. The Radicals Formed in the Reaction between OH-Radicals and Some Sulphoxides and Sulphones

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The short-lived free radicals formed in the reaction between photochemically generated OH-radicals and some aliphatic sulphoxides have been trapped as nitroxide radicals by use of the scavengers 2-methyl-2-nitrosobutanone-3 and *t*-nitrosobutane. The ESR spectra of the nitroxide radicals indicate that alkyl radicals are formed in the reaction between OH-radicals and the sulphoxides by a homolytic cleavage of sulphur-carbon bonds. Radicals were obtained from: $(CH_3)_2SO$, $(CD_3)_2SO$, $(C_2H_5)_2SO$, $(CH_3)(C_2H_5)SO$, $(n-C_3H_7)_2SO$, $(i-C_3H_7)_2SO$, $(CH_3)(n-C_3H_7)SO$, $(n-C_4H_9)_2SO$, $(i-C_4H_9)_2SO$, $(s-C_4H_9)_2SO$, $(n-C_5H_{11})_2SO$, $(n-C_6H_{13})_2SO$, $CH_3-SO-CH_2-CH_2-CH(NH_2)COOH$, $(Ph-CH_2)_2SO$, and $CH_2(CH_2)_3SO$.

The reaction between some of the corresponding sulphones and OH-radicals was also studied. No radicals could be trapped in the reaction with $(CH_3)_2SO_2$, $(C_2H_5)_2SO_2$, and $CH_3-SO_2-CH_2-CH_2-CH(NH_2)COOH$. $(n-C_3H_7)_2SO_2$, $(n-C_4H_9)_2SO_2$, $CH_2(CH_2)_3SO_2$, and $CH_2-CH=CH-CH_2-SO_2$ gave rise to radicals by abstraction of hydrogen atoms.

Nitroso compounds, $R'NO$ (I), possess scavenger properties for free radicals, and react in cross-coupling reactions according to eqn. (1) to form unsymmetric nitroxide radicals (II) stable enough to be detected by ESR spectroscopy.[1-5]

$$R'NO + R\cdot \longrightarrow \underset{\underset{O\cdot}{|}}{R'-N-R} \tag{1}$$

$$\qquad\qquad I \qquad\qquad\qquad II$$
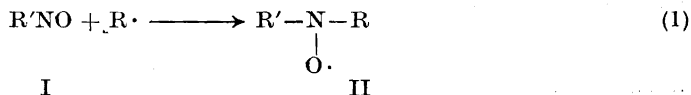
The nitroxide method has been applied in this laboratory for the trapping of short-lived radicals formed in a variety of reactions.[3-5] In these experiments 2-methyl-2-nitrosobutanone-3 and *t*-nitrosobutane were used as nitroso

scavengers (I). In addition to the main triplet splitting caused by the ^{14}N nucleus of the nitroxide group, the ESR spectra of the unsymmetric nitroxide radicals (II) exhibited secondary splittings which originated exclusively from magnetic nuclei of the part of the nitroxide radicals derived from the radical R·. From these splittings it was in many cases possible to settle the structure of the trapped radicals.

The activation of the nitroso scavengers by irradiation with light, and the occurrence of overlapping peaks caused by symmetric nitroxide radicals derived from the scavengers have been fully described elsewhere.[1,3,4]

The ESR spectra of the short-lived radicals formed in the reaction between OH-radicals and a variety of organic substances have been extensively studied during the last years.[6-8] In most of these experiments the OH-radicals were generated in a flow system by reduction of H_2O_2 with Ti^{3+} ions after mixing of reagents before admission of the reaction mixture to the ESR cavity. A somewhat different technique was used by Livingstone and Zeldes,[9,10] who generated the OH-radicals by irradiation of the flowing reaction mixture, which contained added H_2O_2, with UV-light. In this way the need for rapid mixing was avoided but the flow procedure still involved a rather high consumption of the parent material of the radicals.

As the nitroxide method only consumes small quantities of the parent material, as compared with the flow methods, it was thought that the former could be used in the study of the short-lived radicals formed in the reaction with OH-radicals. In these experiments the nitroxide radicals were generated by irradiation with UV-light of a solution containing the parent material, the nitroso scavenger and H_2O_2.[4] The action of light is twofold, i.e. activating the nitroso scavenger by conversion from the dimeric state into the active monomer, and cleaving H_2O_2 into OH-radicals.*

This note describes the nitroxide radicals formed by trapping of the radicals produced in the reaction between OH-radicals and some sulphoxides and sulphones. The reaction between OH-radicals and dimethyl sulphoxide has been previously studied with the flow technique by Dixon et al.[7] who observed the formation of methyl radicals.|

STRUCTURE OF THE TRAPPED RADICALS AND DISCUSSION

The splitting constants of the nitroxide radicals formed in the reaction between photochemically generated OH-radicals and the sulphoxides are collected in Table 1 together with the structure of the trapped radicals as derived from the secondary splittings. Spectra of some of the nitroxide radicals are shown in Figs. 1—5. Most of the experiments were performed with 2-methyl-2-nitrosobutanone-3 as the scavenger, but t-nitrosobutane was used in some cases in which the resolution of the secondary splittings was found to

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* The equilibrium of the scavenger t-nitrosobutane is shifted more towards the monomer as compared with 2-methyl-2-nitrosobutanone-3, and at room temperature the former scavenger is therefore able to react directly without any previous irradiation.[5] As the reaction mixtures here concerned had to be irradiated for generating the OH-radicals there was in general no advantage in using t-nitrosobutane in place of 2-methyl-2-nitrosobutanone-3.
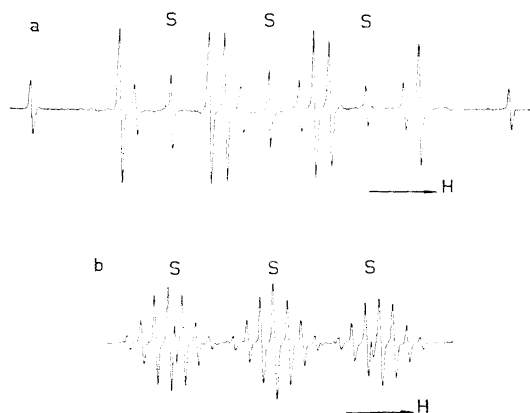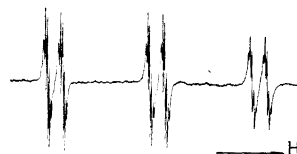
Fig. 1. ESR spectrum of the nitroxide radicals formed by tapping of methyl radicals produced in the reaction between photochemically generated OH-radicals and dimethyl sulphoxide at room temperature. Solvent: H_2O. Scavenger: 2-methyl-2-nitrosobutanone-3. S=lines from the symmetric nitroxide radicals derived from the scavenger. a. $CH_3\cdot$ radicals from $(CH_3)_2SO$; b. $CD_3\cdot$ radicals from $(CD_3)_2SO$.

be somewhat better with this substance (Figs. 4 and 5). The splitting constant a^N is somewhat larger for the nitroxide radicals formed from *t*-nitrosobutane as compared with that obtained by use of 2-methyl-2-nitrosobutanone-3.[6] No radicals except the symmetric nitroxide radicals derived from the scavenger were obtained without the addition of H_2O_2.

It is evident that radicals of the general structure $R\cdot$ are formed from the sulphoxides, R_2SO, in the reaction with OH-radicals by a cleavage of carbon-
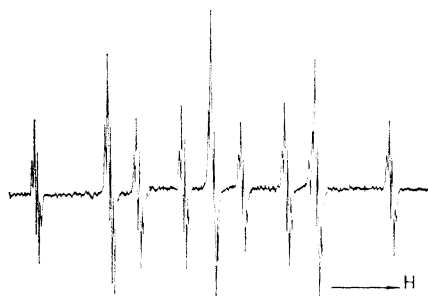
Fig. 2. ESR spectrum of the nitroxide radicals formed by trapping of ethyl radicals produced in the reaction between photochemically generated OH-radicals and $(C_2H_5)_2SO$ at room temperature. Solvent: H_2O Scavenger: 2-methyl-2-nitrosobutanone-3.

Fig. 3. ESR spectrum of the nitroxide radicals formed by trapping of $(CH_3)_2CH\cdot$ radicals produced in the reaction between photochemically generated OH-radicals and $(i\text{-}C_3H_7)_2SO$ at room temperature. Solvent: H_2O. Scavenger: 2-methyl-2-nitrosobutanone-3.
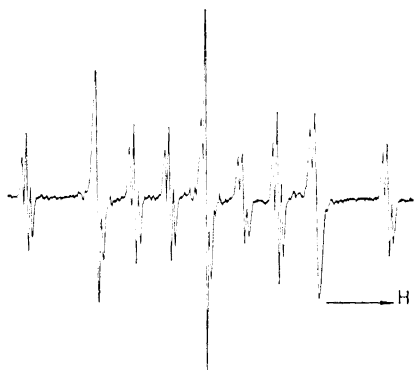
Fig. 4. ESR spectrum of the nitroxide radicals formed by trapping of the radical $R'' - CH_2 - CH_2 \cdot$ produced in the reaction between photochemically generated OH-radicals and tetrahydrothiophene-1-oxide, $CH_2(CH_2)_3SO$. Scavenger: *t*-nitrosobutane. Room temperature.
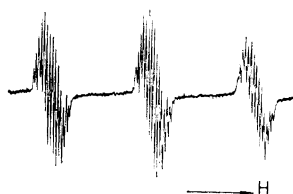

Fig. 5. ESR spectrum of the nitroxide radicals formed by trapping of the radicals produced by hydrogen abstraction in the reaction between photochemically generated OH-radicals and sulpholane, $CH_2(CH_2)_3SO_2$. Scavenger: *t*-nitrosobutane. Room temperature.

sulphur bonds. Thus, methyl, ethyl, propyl, isopropyl, butyl, isobutyl, *s*-butyl, pentyl, hexyl, and benzyl radicals were formed from the corresponding symmetric sulphoxides. Analogously, the unsymmetric sulphoxides, $R^1 - SO - R^2$, gave rise to two different radical species, $R^1 \cdot$ and $R^2 \cdot$, as seen from the superposition spectra obtained with methyl ethyl sulphoxide, methyl propyl sulphoxide and methionine sulphoxide. No radicals could be detected in the reaction with diallyl sulphoxide, diphenyl sulphoxide and bis (*p*-chlorophenyl) sulphoxide. Methyl phenyl sulphoxide gave rise only to the trapping of methyl radicals.

The splitting constants a^H (Table 1) of the unsymmetric nitroxide radicals obtained in the reaction with dimethyl and diethyl sulphoxide are not very different from those reported by Hudson and Hussein [11] for the corresponding symmetric nitroxide radicals (dimethyl nitroxide: $a^H = 14.7$ g, diethyl nitroxide: $a_\alpha^H = 11.2g$, $a_\beta^H = 0.32$ g). This agreement supports the conclusion that alkyl radicals are split off from the sulphoxides in the reaction with OH-radicals, and that the radicals trapped do not contain any sulphur atom.

The results indicate that alkyl radicals are easily trapped by the nitroxide method, and that the nitroxide radicals formed in this case are stable enough to be detected by ESR spectroscopy, even in a medium containing H_2O_2 and OH-radicals, and in the presence of UV-light. It could not be decided whether the failure to observe any radicals in the reaction with diallyl sulphoxide depended on a decomposition of the parent substance, insufficient formation of the allyl radical, or if the allyl-nitroxide radicals were too instable. The reason for our failure to trap any aromatic radicals is not clear but it may involve steric factors, or a lower reactivity of aromatic radicals as compared with that of alkyl radicals, in which the unpaired electron is highly localized.

Table 1. Splitting constants in gauss of the unsymmetric nitroxide radicals $(CH_3)_2(COCH_3)\overset{|}{\underset{O\cdot}{C}}-N-R$ formed from 2-methyl-2-nitrosobutanone-3 and the radicals R · produced in the reaction between OH-radicals and some sulphoxides.

Parent substance	a^N	a_α^H	a_β^H	a^D	Trapped radical R ·
$(CH_3)_2SO$	15.9	13.5(q)			$\overset{\cdot}{C}H_3$
$(CD_3)_2SO$	16.0			2.1(s)	$\overset{\cdot}{C}D_3$
$(C_2H_5)_2SO$	15.7	11.3(t)	0.3(q)		$\overset{\cdot}{C}H_2-CH_3$
$(n\text{-}C_3H_7)_2SO$	15.3	10.8(t)	0.6(t)		$\overset{\cdot}{C}H_2-CH_2-CH_3$
$(i\text{-}C_3H_7)_2SO$	15.6	2.3(d)	0.3(s)		$\overset{\cdot}{C}H(CH_3)_2$
$(n\text{-}C_4H_9)_2SO$	15.0	10.5(t)	0.5(t)		$\overset{\cdot}{C}H_2-CH_2-C_2H_5$
$(i\text{-}C_4H_9)_2SO$	1.56	11.2(t)	0.7(d)		$\overset{\cdot}{C}H_2-CH(CH_3)_2$
$(s\text{-}C_4H_9)_2SO$	15.3	2.2(d)	unresolved		$\overset{\cdot}{C}H(CH_3)(C_2H_5)$
$(n\text{-}C_5H_{11})_2SO$	15.1	10.3(t)	0.5(t)		$\overset{\cdot}{C}H_2-CH_2-C_3H_7$
$(n\text{-}C_6H_{13})_2SO$	15.0	10.4(t)	0.5(t)		$\overset{\cdot}{C}H_2-CH_2-C_4H_9$
$(CH_3)(C_2H_5)SO$	16.0	13.6(q)			$\overset{\cdot}{C}H_3$
	15.7	11.3(t)	0.3(q)		$\overset{\cdot}{C}H_2-CH_3$
$(CH_3)(n\text{-}C_3H_7)SO$	16.1	13.7(q)			$\overset{\cdot}{C}H_3$
	15.7	11.2(t)	0.6(t)		$\overset{\cdot}{C}H_2-CH_2-CH_3$
$CH_3-SO-CH_2-CH_2-CH(NH_2)$	16.1	13.7(q)			$\overset{\cdot}{C}H_3$
$\qquad\qquad\qquad\qquad\overset{|}{COOH}$	15.5	12.0(t)	0.5(t)		$\overset{\cdot}{C}H_2-CH_2-R''$
$(Ph\text{-}CH_2)_2SO^*$	14.5	8.3(t)			$\overset{\cdot}{C}H_2-Ph$
$CH_2(CH_2)_3SO$	15.5	11.1(t)	0.5(t)		$\overset{\cdot}{C}H_2-CH_2-R''$

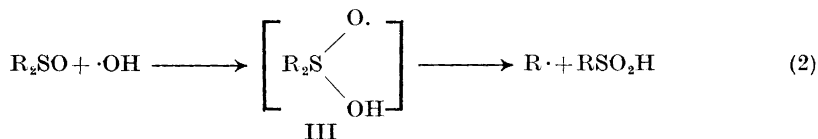*Solvent: CH_2Cl_2. d=doublet, t=triplet, q=quartet, s=septet.

The reaction between OH-radicals and some sulphones was also studied by the nitroxide method. In general, the sulphones behaved very differently as compared with the corresponding sulphoxides. No radicals could be trapped in the reaction with $(CH_3)_2SO_2$, $(C_2H_5)_2SO_2$, and $CH_3-SO_2-CH_2-CH_2-CH(NH_2)COOH$. $(n\text{-}C_3H_7)_2SO_2$ and $(n\text{-}C_4H_9)_2SO_2$ gave rise to a secondary doublet of about 2 gauss further split into a narrow triplet, evidently caused by the trapping of radicals formed by abstraction of one of the hydrogen atoms from a methylene group. The cyclic sulphones sulpholane and sulpholene also gave rise to radicals by hydrogen abstraction. The nitroxide radicals formed by trapping of these radicals exhibited a number of incompletely resolved secondary structures which are the result of an interaction with different sets of axial and equatorial hydrogen atoms. Fig. 5 shows the spectrum obtained with sulpholane. This spectrum is to be compared with that obtained from the corresponding sulphoxide, tetrahydrothiophene-1-oxide, Fig. 4. The latter spectrum indicates the formation of a radical of the

structure ·CH₂—CH₂—R″ by cleavage of one of the carbon-sulphur bonds and opening of the ring.

In addition to the alkyl radicals (see Table 1), a further radical species was trapped in the reaction with the sulphoxides $(n\text{-}C_4H_9)_2SO$, $(n\text{-}C_5H_{11})_2SO$, and $(n\text{-}C_6H_{13})_2SO$. The latter radical species gave rise to a secondary doublet structure with a splitting constant almost identical to that obtained with the aliphatic sulphones. In order to find out whether these radicals originated from sulphones present in the sulphoxides prior to the reaction, or from sulphones formed in the reaction by oxidation of the sulphoxides, most of the substances and the reaction mixtures were analyzed by the technique of combined gas-liquid chromatography and mass spectrometry. The results indicated that the sulphoxides contained only small amounts of the corresponding sulphones (0.5—2 %). Addition of H_2O_2 to a water solution of the sulphoxides without any irradiation increased the content of sulphones to about 10 %. Irradiation with UV-light subsequent to the addition of H_2O_2 resulted in a large increase of the sulphone content. After 10 min of irradiation the amount of sulphones was nearly equal to that of the sulphoxide.

It is thus probable that the radical species which give rise to the secondary doublet splitting observed with some of the sulphoxides are derived from the corresponding sulphones formed during the reaction. With an increasing length of the alkyl chain of the sulphoxides radicals might also be formed by abstraction of a hydrogen atom in analogy with the radical formation observed in case of the sulphones. A further explanation involves an intramolecular shift of a hydrogen atom in the primary alkyl radicals from a methylene group to the carbon atom at the end of the radical molecule. It is believed, however, that the former mechanism, i.e. oxidation of the sulphoxides to sulphones, is the dominating one.

Dixon et al.[7] (see also Norman and Gilbert [8]) have suggested a mechanism for the reaction between OH-radicals and dimethyl sulphoxide which involves an attack by OH-radicals on the sulphur atom. In view of the results obtained here with a number of other sulphoxides this mechanism may be generalized:

$$R_2SO + \cdot OH \longrightarrow \left[R_2S \overset{\displaystyle O \cdot}{\underset{\displaystyle OH}{\diagup\diagdown}} \right] \longrightarrow R \cdot + RSO_2H \qquad (2)$$

III

This reaction is evidently not possible in the case of sulphones where the sulphur atom is bonded already to four atoms, a situation which prevents the formation of the intermediate compound, III, in agreement with the experimental results.

EXPERIMENTAL

Dimethyl sulphoxide (Fisher p.a.), dimethyl sulphoxide-d_6 (Merck Spectrograde Quality), methionine sulphoxide, methionine sulphone, and bis(p-chlorophenyl) sulphoxide (Fluka) were used as supplied. Most of the other sulphoxides here used were prepared according to Leonard and Johnson [12] by oxidation of the corresponding mono-sulphides with sodium periodate at 0°C, a procedure which gives products with a minimum

contamination of sulphones. The purity of the sulphoxides and the sulphones, and the composition of the reaction mixture were analyzed by the technique of combined gas-liquid chromatography and mass spectrometry (2 m column: 5 % Carbowax 20-M on Diatoport S, 80/100 mesh at 170°C; see also Refs. 13 and 14). Dimethyl sulphone was prepared as described by Lister and Sutton,[15] diethyl sulphone according to Bonner and Drisko.[16] Dipropyl sulphone and sulpholane were purified by fractional vacuum distillation (0.5 m spinning-band column). The nitroso scavenger 2-methyl-2-nitrosobutanone-3 was prepared as described by Aston et al.[17] and t-nitrosobutane according to Emmons.[18]

The radicals were prepared by dissolving the sulphoxide or sulphone in water, or a mixture of water and a small amount of t-butanol, together with the nitroso scavenger (0.01 M), and adding a few drops of 38 % H_2O_2. The samples were then irradiated in situ in the ESR cavity. The light-source was a high pressure mercury lamp (Osram HBO-200). It was also possible to prepare the radicals directly by oxidation in situ of the corresponding monosulphides to the sulphoxides after addition of a small amount of acetic acid.

The ESR spectra were obtained with a Varian 100 kc spectrometer and a 9" magnet equipped with the "Fieldial" magnetic field regulator. Most of the spectra were recorded at ambient room temperature with samples contained in a flat aqueous solution cell. In some cases it was necessary to perform the measurements at a somewhat lower temperature ($+10$°C) in order to increase the life-time of the radicals. These measurements were taken with the aid of a special flat cell (Varian V-4548-1) small enough to fit into the dewar of the Varian variable temperature accessory. Splitting constants are quoted relative to Fremy's radical (13.0 gauss).

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