Secondary Radicals in the Autoxidation of Hydroquinones and Quinones

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The autoxidation of hydroquinones and quinones in strongly alkaline solution gives rise to radical intermediates other than the expected semiquinones. These 'secondary' radicals, which are derived from 1,2,4-trihydroxybenzene, can be characterised by means of e.s.r. spectroscopy. Different isomeric radicals may be formed, depending on the solvent, and apparently these may reduce any excess of quinone present to the corresponding semiquinone.

SEMIQUINONES were among the first radicals to be investigated by means of e.s.r. spectroscopy because they are easily produced and can generally be obtained in relatively high concentrations. A wide range of *ortho*-, *meta*-, and *para*-semiquinones have been studied.[1-4] However, the formation of semiquinones is only the first stage in the autoxidation of dihydric phenols in alkaline solution. Further stages can profitably be followed by changes in the e.s.r. spectra of the solutions. For example, Stone and Waters [4] have observed semiquinones of trihydroxybenzenes in the autoxidation of some substituted catechols. It is surprising that this has not been reported before, in any detail, in relation to the autoxidation of hydroquinones, since slight variations in alkalinity, concentration, and in the composition of the solvent lead to radicals derived from 1,2,4-trihydroxybenzenes rather than the expected *p*-semiquinones.[5] These 'secondary' radicals can be characterised from their e.s.r. spectra which are frequently well defined and easily resolved.

High concentrations of semiquinones can be obtained just as easily from quinones as from the corresponding hydroquinones,[5,6] in spite of the fact that in the latter

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[1] G. K. Fraenkel and B. Venkataraman, *J. Amer. Chem. Soc.*, 1955, **77**, 2707.

[2] R. Hoskins, *J. Chem. Phys.*, 1955, **23**, 1975.

[3] T. J. Stone and W. A. Waters, *J. Chem. Soc.*, 1964, 4302.

[4] T. J. Stone and W. A. Waters, *J. Chem. Soc.*, 1965, 1488.

[5] P. Ashworth and W. T. Dixon, *Chem. Comm.*, 1971, 1150.

[6] D. C. Reitz, J. R. Hollahan, F. Dravnieks, and J. E. Wertz, *J. Chem. Phys.*, 1961, **34**, 1457.

case there is aerial oxidation, and in the former an overall reduction. This apparent paradox can be resolved by postulating intermediates capable of reducing quinones and it seems that these may well be the secondary radicals which we have been investigating. Under certain conditions we observed spectra which appear to arise from products of coupling reactions and we will refer to these as ' tertiary ' radicals.

The radicals we obtained and their e.s.r. coupling constants are shown in the Table. In practice the observation of each secondary radical was favoured by certain conditions. A working guide for producing the radicals is as follows.

Primary Radicals.—These are produced in even faintly alkaline solutions of hydroquinones and quinones and are more stable in alcoholic media. The spectra are best observed by use of a flow system and in this case a solution of the hydroquinone (0·005M) in ethanol was allowed to flow against 1% sodium hydroxide solution.

Secondary Radicals.—Although these are formed in dilute alkali, more concentrated alkali is usually required to obtain good e.s.r. spectra. Different isomeric radicals may be obtained depending on the solvent (see Table) and sometimes mixtures of these radicals are observed. The techniques used for obtaining e.s.r. spectra of the secondary radicals were as follows. (*a*) A solution of the hydroquinone (*ca.* 0·01M) in the appropriate solvent was added to 10% sodium hydroxide solution. This technique was particularly effective for the monosubstituted and the 2,3-dimethylhydroquinones. (*b*) The hydroquinone or quinone (*ca.* 0·005M) was left in 1% sodium hydroxide solution for *ca.* 1 h and then an equal volume of 10% sodium hydroxide was added. This was effective for the disubstituted compounds where method (*a*) gave only primary radicals. (*c*) A solution of the quinone (*ca.* 0·01M) was added dropwise to an excess of alkali (5% NaOH).

The solutions were immediately transferred to an aqueous cell in the cavity of an e.s.r. spectrometer. The spectra observed were then normally uncontaminated by the presence of other radicals and subsequent interpretation was made easier. The exact values of the coupling constants of the secondary radicals were found to depend on the nature of the solvent, as observed for primary radicals.[7]

Coupling constants of primary (as I) and secondary (as II) radicals

	Coupling constants/G								
	Primary radical (in 50% aq. EtOH)					Secondary radical			
Parent hydroquinone:	a_2	a_3	a_5	a_6		a_3	a_5	a_6	Solvent
Hydroquinone	← 2·37 →					0·60	4·98	1·34	Water
Methyl	2·12 (Me) (quartet)	1·76	2·61	2·41	A	0·58	5·12 (Me)	0·69	50% aq. EtOH
					B	0·55	4·15	0·95 (Me)	Water
Ethyl	2·02 (Et) (triplet)	1·74	2·53	2·53	A	0·54	4·56 (Et)	0·71	50% aq. EtOH
					B	0·56	4·14	1·08 (Et)	Water
t-Butyl		1·65	2·89	2·12	A	0·52	0·16 * (Bu^t) (septet)	0·84	Water
					B	0·66	4·02		Water
2,3-Dimethyl	1·74 (Me)	1·74 (Me)	2·62	2·62		0·55	4·70 (Me)	0·55 (Me)	Water
2,6-Dimethyl	2·09 (Me)	1·93	1·93	2·09 (Me)		0·97 (Me)	5·20 (Me)	0·72	50% aq. DMF †
2,5-Dimethyl	2·34 (Me)	1·80	2·34 (Me)	1·80		0·88 (Me)	4·20	0·98 (Me)	50% aq. DMF †
5-Isopropyl-2-methyl	2·18 (Me)	1·76	1·92 (Pr^i) (doublet)	1·46		0·92 (Me)	4·20	0·75 (Pr^i) (doublet)	Water

* Splitting from 6 equivalent protons showing that the t-butyl group is not freely-rotating (C. Trapp, C. A. Tyson, and G. Giacometti, *J. Amer. Chem. Soc.*, 1968, **90**, 1394). † Dimethylformamide.

Characterisation of the Radicals.—We felt that the e.s.r. spectra alone did not enable us to deduce with certainty the nature of the secondary radicals, so we tried to gather supporting evidence. The most obvious method was to synthesise the 1,2,4-trihydroxybenzene derivatives which on autoxidation should give semiquinones which correspond to the secondary radicals. We did this for three hydroquinones by means of the sequence[8] (1). When R = H we observed the same eight-line spectrum (from three doublet splittings) as that ascribed to the secondary radical of hydroquinone

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[7] E. W. Stone and A. H. Maki, *J. Chem. Phys.*, 1962, **36**, 1944.

[8] E. B. Vliet, *Org. Synth.*, Coll. Vol. I, 317.

(see Figure 2). When R = Me we observed the same spectrum as that of radical A from 2,5-dihydroxytoluene. When R = Bu^t we observed the same spectrum as that of radical A from 1,4-dihydroxy-2-t-butylbenzene. The three radicals just discussed were also reproduced by adding solutions of catechol and the 4-substituted catechols (0·01M) dropwise to 5% sodium hydroxide. If 5% alkali is added to a more concentrated solution of catechol (0·05M) a different type of radical is observed along with the *o*-semiquinone, *i.e.*, the dimer observed by Stone and Waters.[9]

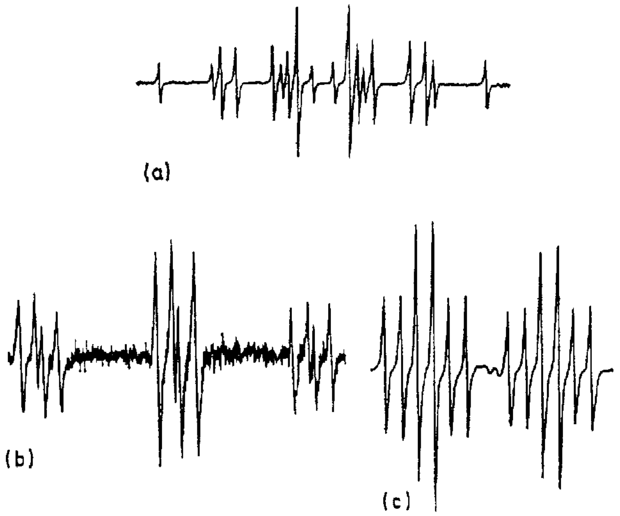


FIGURE 1 The e.s.r. spectra obtained from alkaline solutions of ethylhydroquinone: (a) primary radical in 50% ethanol, 1% NaOH; (b) secondary radical A in 50% ethanol, 10% NaOH; (c) secondary radical B in 10% NaOH

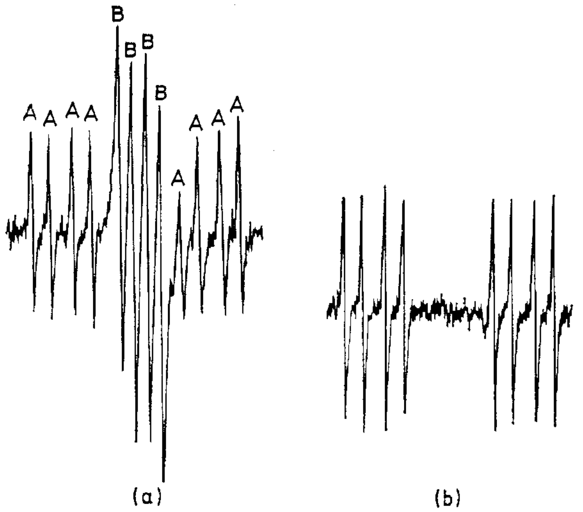
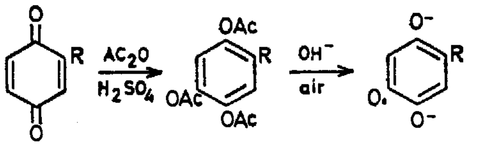


FIGURE 2 (a) Spectrum from hydroquinone (0·001M) in 5% NaOH; lines A due to secondary radical; lines B due to tertiary radical, (b) spectrum from 1,2,4-triacetoxybenzene in 5% NaOH



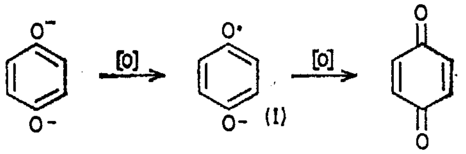
(1)

Having thus proved the identity of these three radicals we reasonably infer the structure of other secondary radicals on the basis of their e.s.r. spectra and a knowledge of the starting material. The following rules seem to apply: (i) Spin densities *para* with respect to oxygen atoms are high (proton coupling constants *ca.* 4—5 G); (ii) methyl proton coupling constants tend to be slightly higher than corresponding aromatic proton splittings; (iii) spin densities on ring carbon atoms between those attached to two oxygen atoms are apparently lower than those on carbon atoms adjacent to only one carbon–oxygen linkage.

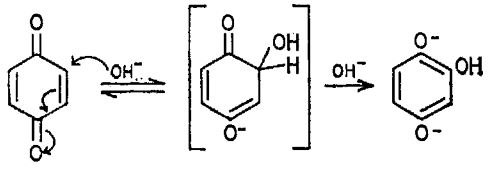
On the basis of these empirical rules we could consistently account for the observed hyperfine splittings. Our assignments imply that hydroxyl is introduced into the ring at the least hindered position, as expected.

DISCUSSION

Since our secondary radicals are derived from 1,2,4-trihydroxybenzenes, we now ask how they arise. It is of interest that both hydroquinones and quinones can be used as starting materials.



(2)



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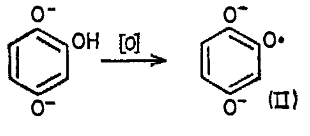

(4)

It is not difficult to arrive at a feasible reaction scheme. The first steps (2) in the autoxidation of hydroquinone lead to benzoquinone. We are not concerned here with coupling products so the next stage is the introduction of a further oxygen atom into the ring. Here we are helped by two well established reactions in which no overall oxidation of the quinone takes place. First, there is addition of HCl to give chloroquinol,[10] and secondly there is the Thiele acetylation[8,11] discussed above. We might, therefore, expect a base-catalysed addition (3) of the elements of water. If this is so there

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[9] T. J. Stone and W. A. Waters, *J. Chem. Soc.*, 1964, 408.

[10] J. B. Conant and L. F. Fieser, *J. Amer. Chem. Soc.*, 1923, **45**, 2194.

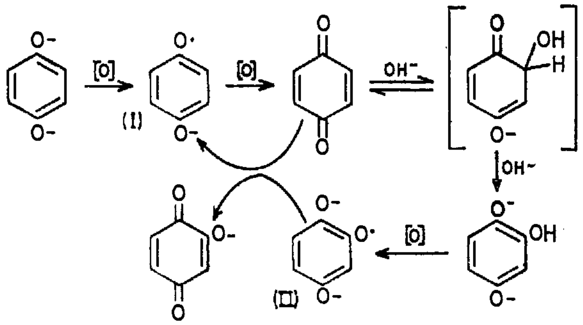
[11] J. Thiele and E. Winter, *Annalen*, 1900, **311**, 341.

must then be further attack by oxygen (4) to give the semiquinone of trihydroxybenzene.

We can now rationalise the observed reduction of quinones when their alkaline solutions are shaken in air. It appears that they are reduced by the corresponding secondary radicals. This possibility is strengthened by our experiments on quinones. When the quinone is always present in high concentration (*e.g.*, 0·01M), the primary radical is observed in alkaline solution, whereas if the concentration of the quinone is kept low (*i.e.*, by adding a 0·01M solution dropwise to alkali) a secondary radical is observed.

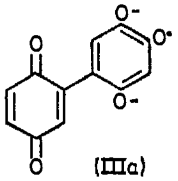
Similarly when an alkaline solution of benzoquinone (*ca.* 0·01M) is left, the signal due to the semiquinone decays. After *ca.* 1 h, addition of fresh alkali leads to the secondary radical, showing that the trihydroxybenzene derivative must have replaced the quinone.

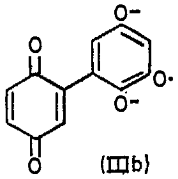
Therefore, we suggest the Scheme for the cycle of reactions leading to the formation of primary and secondary radicals.[12] Both primary and secondary radicals may be destroyed by further oxidation, by dimerisation, or by coupling with, for example, benzoquinone. The further oxidation stage was demonstrated by an experiment in which a solution of t-butylhydroquinone in 5% sodium hydroxide was left open to the air for a day. When the mixture was allowed to flow against dithionite the spectrum of a mixture of both secondary radicals (see Table) was observed showing that the hydroxyquinone derivatives must have been formed. There was no trace of the spectrum of t-butylsemiquinone.

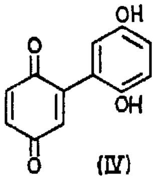


SCHEME

We have obtained a number of well defined spectra which are probably due to coupled products of the reaction. For example the quartet which appears in the secondary spectrum from hydroquinone or benzoquinone (Figure 2) appears to arise from radical (IIIa) in which there is no delocalisation around the second ring. The coupling constants, 0·90 and 0·45 G, are similar to those obtained by Reitz *et al.*[6] starting from the quinol (IV) but they apparently saw a further splitting of 0·1 G. We did not observe this small splitting but we feel justified in our assignment because, first, the magnitudes of the coupling constants are just those expected for a trihydroxy-compound and not for a substituted semiquinone (*cf.* radical A from t-butylhydroquinone in the Table). Secondly, under the conditions of their experiment (10% NaOH), we would expect a secondary-type radical.


(IIIa)


(IIIb)


(IV)

If we add 10% sodium hydroxide to a solution of benzoquinone in 50% dimethylformamide we observe a different quartet (splittings 4·52 G, 0·70 G) which we ascribe to the isomeric radical (IIIb). However, the situation with regard to these tertiary radicals is still not clear and further study is required.

EXPERIMENTAL

E.s.r. spectra were obtained with a Varian E-4 instrument by use of both flow and static methods.

Quinones could be obtained by oxidation of the corresponding hydroquinones with chromic anhydride in 60% acetic acid. The reverse process was effected by reducing the quinone with zinc and 25% hydrochloric acid.

When neither the quinone nor the hydroquinone were available the corresponding phenol was oxidised to the quinone by use of Frémy's salt, according to the method of Tauber and Rau.[13] 4-Substituted catechols were prepared analogously,[14] the *o*-quinones so produced being reduced by zinc and hydrochloric acid.

Triacetoxybenzene derivatives were prepared by the Thiele acetylation [8] and were used directly since the acetyl groups were hydrolysed off by the alkaline medium.

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[12] M. Eigen and P. Matthies, *Chem. Ber.*, 1961, **94**. 3309.
[13] H.-J. Teuber and W. Rau, *Chem. Ber.*, 1953, **86**, 1036.
[14] H.-J. Teuber and G. Staiger, *Chem. Ber.*, 1955, **88**, 802.