

OXIDATION MECHANISM OF 2-ALKYLHYDROQUINONES INVESTIGATED BY THE EPR METHOD

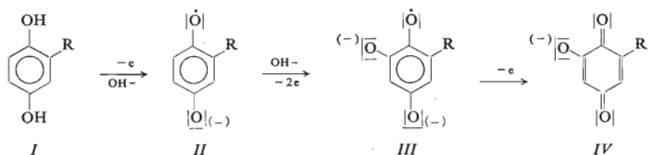
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Oxidation mechanism of 2-alkylhydroquinones in an alkaline medium has been investigated. During the oxidation in an aqueous solution of potassium hydroxide, 2-isopropyl, 2-butyl, and 2-sec-butylhydroquinone yield primary radicals of type *II* which are gradually transformed into secondary radicals of type *III*. Under the same conditions, 2-methylhydroquinone undergoes further oxidation and radical *VII* was identified in the reaction mixture.

Our earlier papers^{1,2} have been dealing with the investigation of the oxidation mechanism of 2-tert-alkylhydroquinones and 4-tert-alkylpyrocatechols in an alkaline medium. In the work reported here, the investigation of the oxidation mechanism has been extended to some further 2-alkylhydroquinones. During the oxidation of 2-methyl-(*Ia*), 2-isopropyl-(*Ib*), 2-butyl-(*Ic*), and 2-sec-butylhydroquinones (*Id*) with oxygen in the measuring cavity of an EPR spectrometer in a flow arrangement, we recorded EPR spectra in both aqueous and 75% aqueous-methanol medium. These spectra belonged to primary radical of the corresponding *para*-benzosemiquinones *Ila–Ild*, similarly to the oxidation of 2-tert-butylhydroquinone (splitting constants *cf.* Table I). After the flow of the reaction mixture through the measuring cavity of the spectrometer has been stopped, the intensity of the spectra rapidly decreases, and spectra of secondary radicals appear in the aqueous medium. The spectrum obtained during the oxidation of 2-methylhydroquinone is identical with that described for the anion-radical of 1,2,4-trihydroxy-6-methylbenzene³; the radical involved is therefore radical *IIIa* (Scheme 1). An analysis of spectra of the secondary radicals obtained during the oxidation of the remaining three alkyl derivatives of hydroquinone also leads to the conclusion that the radicals involved are *IIIb–IIIId*. With the exception of the oxidation of 2-methylhydroquinone, no further radical intermediates could be recorded in the aqueous solution of potassium hydroxide; it can be said, therefore, that the autoxidation of these derivatives of hydroquinone is qualitatively identical with that of the autoxidation of the 2-tert-alkyl derivatives. The fact that in contrast with the oxidation of 2-tert-butylhydroquinone¹ no hydroxybenzoquinones *IVb* to *IVd* could be isolated from the reaction mixture obtained by the oxidation of alkylhydroquinones *Ib–Id* can be explained by their limited stability under the working



a, R = CH₃

b, R = CH(CH₃)₂

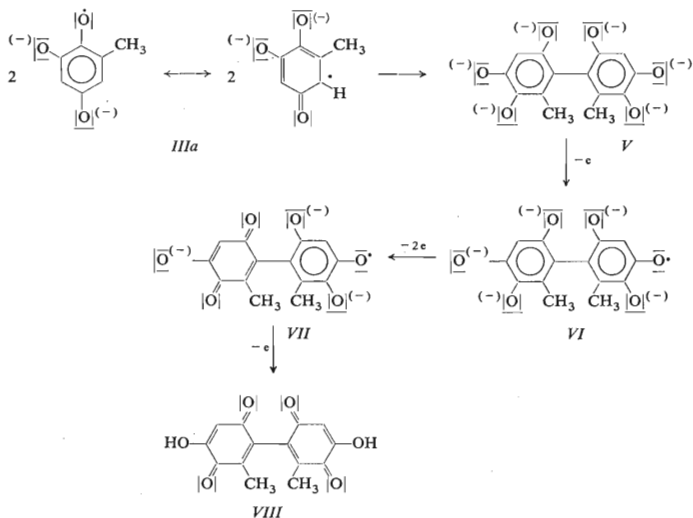
c, R = CH₂CH₂CH₂CH₃

d, R = CH₃CH(C₂H₅)

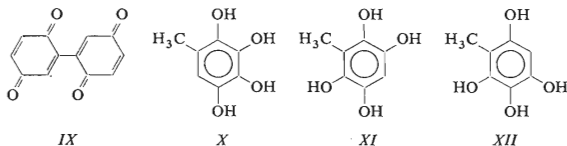
e, R = C(CH₃)₃

SCHEME 1

conditions, as well as by transformations of a non-radical character. Formation of small amounts of the above hydroxybenzoquinones, along with three to four other substances, was proved by means of thin layer and paper chromatography. The primary radicals *Ila*–*Ild* yield in a water–methanol medium a complex mixture of secondary radicals which have not been subjected to further analysis.



SCHEME 2



During the oxidation of 2-methylhydroquinone in an aqueous solution of potassium hydroxide we recorded more radical intermediates than during the oxidation of 2-alkylhydroquinones *Ib–Ie*. If the measurements are made in a stationary arrangement, another spectrum appears in the centre of the spectrum of the secondary radical after about ten minutes (Figs 1*a–c*). After complete disappearance of the spectrum of the secondary radical, the new spectrum consists of 15 equidistant lines (Fig. 1*d*). Spectroscopic measurements carried out by Corbett⁴ have shown that one of the main products of oxidation of 1,2,4-trihydroxy-6-methylbenzene is diquinone *VIII* (Scheme 2), whose formation in the reaction mixture is probably preceded by dimerization of radical *IIIa*. We thus assumed that further oxidation of 2-methylhydroquinone could give rise to the formation of a radical derived from this dimer.

2,2'-Dimethylbiphenyl-3,3',4,4',6,6'-hexol (*V*) was therefore prepared as a model compound; it was oxidized under the same conditions as alkylhydroquinones under investigation. During oxidation in the flow arrangement or immediately after both components of the reaction mixture had been mixed, a spectrum was recorded consisting of nine equidistant lines. In the course of further oxidation, this spectrum was transformed into a far more intensive spectrum, identical with the fifteen-line spectrum recorded during the oxidation of 2-methylhydroquinone after the decay of the spectrum of the secondary radical. An analysis of the spectra thus obtained has shown that the hyperfine structure of the nine-line spectrum is due to an interaction of the unpaired electron with eight equivalent protons within limits of experimental error, and the hyperfine structure of the fifteen-line spectrum is due to an interaction of the unpaired electron with six equivalent protons and two equivalent protons, the splitting constant of the septet being twice as large as the splitting constant of the triplet. The facts described above together with the finding that the final oxidation product of biphenylhexol *V* is the dimeric hydroxyquinone *VIII* led to the conclusion that the radical characterized by the nine-line spectrum is radical *VI*, while that with the fifteen-line spectrum is radical *VII* arising from *VI* by the loss of another two electrons (Scheme 2). Interactions of the unpaired electron with the protons of the aromatic ring in positions 5,5' and with the protons of the methyl groups of radical *VI* are characterized by the identical splitting constants, similarly to the anion-radical of 1,2,4-trihydroxy-5,6-dimethylbenzene³. The possibility of a rapid electron exchange between the aromatic rings of radicals of type *VII* was confirmed by Stone and Maki⁵, who found by analyzing the spectrum of a radical prepared by electrochemical reduction of diquinone *IX* that in this radical the unpaired electron interacted with three pairs of equivalent protons. We made an attempt to support the interpretation of the recorded spectra by calculations of the spin densities in radicals *VI* and *VII* using McLachlan's method; we applied parameters suggested by Lott and coworkers³ for the anion radicals of methyl substituted 1,2,4-trihydroxybenzenes and varied at the same time the resonance integral of the C₁—C_{1'} bond during the calculations, thus trying to respect the possible nonplanarity of both radicals. It is evident from the results given in Table II that in positions 2,2', in which the

methyl groups are bonded, the calculated spin densities are higher for radical *VII* than for radical *VI*. The ratio of spin densities in positions 2,2' and 5,5' in radical *VI* calculated for values of angle $\theta = 30-50^\circ$ is approximately unity which is in agreement with the ratio of values of the respective splitting constants. However, the ratio of spin densities calculated in positions 2,2' and

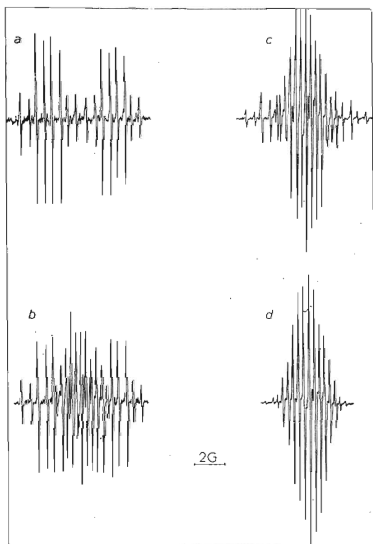


FIG. 1

EPR Spectra of the Reaction Mixture Recorded During Air Oxidation of 2-Methylhydroquinone ($5 \cdot 10^{-3} M$) in 20% Aqueous KOH in the Stationary Arrangement

Time of recording after mixing of the components: *a* immediately after mixing — spectrum of the secondary radical *IIIa*; *b* 1 h — superposition of the spectra of the secondary and tertiary radicals — gain decreased 1.8 times compared with *a*; *c* 2 h — superposition of the above spectra — gain decreased 3.2 times compared with *a*; *d* three h — spectrum of radical *VII* — gain decreased 3.2 times compared with *a*.

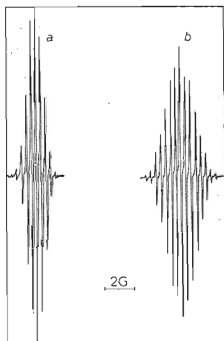


FIG. 2

EPR Spectra of Radicals *VI* (*a*) and *VII* (*b*) Obtained by Air Oxidation of 2,2'-Dimethyl-3,3',4,4',6,6'-Biphenylhexol in 20% Aqueous KOH in the Stationary Arrangement

5,5' of radical *VII* is too high in comparison with the ratio of values of the respective splitting constants. No better quantitative agreement with the experiment was attained probably because the method of calculations applied here was rather crude for the comparatively complex molecule under study.

It follows from the investigation of the oxidation of biphenylhexol *V* that during the oxidation of 2-methylhydroquinone in aqueous potassium hydroxide, radical *VI* is probably formed as the tertiary one, and radical *VII* is formed as the quaternary one. Formation of radical *VI* in the reaction mixture could not be proved, probably because in the first stages of superposition of the new spectrum upon the spectrum of the secondary radical only the central part of the former can be seen (Fig. 1); moreover, as can be seen from Fig. 2, the central parts of the spectra of radicals *VI* and *VII* are very similar. The latest isolated and identified oxidation product of biphenylhexol *V* (investigated as a model compound) is diquinone *VIII*, which undergoes only a slow further oxidation with oxygen alone. If the oxidation occurs in the presence of 0.5% H_2O_2 , it proceeds much faster yielding a mixture of products, one of them red and another greenish-yellow; their composition has not been investigated. The fact that diquinone *VII* undergoes further oxidation with hydrogen peroxide can help us to explain why this diquinone was present in the mixture of the autoxidation pro-

TABLE I
Splitting Constants of Radicals in 20% KOH (in Gauss)

| Radical | a_2^{Alky1} | a_3^H | a_5^H | a_6^H |
|-------------|-----------------------|-----------------|-------------------|-----------------|
| <i>Ila</i> | 2.10 ± 0.04^a | 1.80 ± 0.03 | 2.55 ± 0.05 | 2.55 ± 0.05 |
| <i>Ilb</i> | 1.35 ± 0.03^b | 1.78 ± 0.03 | 2.54 ± 0.04 | 2.54 ± 0.04 |
| <i>Ilc</i> | 1.67 ± 0.03^c | 1.67 ± 0.03 | 2.50 ± 0.04 | 2.50 ± 0.04 |
| <i>Ild</i> | 0.93 ± 0.02^d | 1.76 ± 0.03 | 2.50 ± 0.04 | 2.50 ± 0.04 |
| <i>Ile</i> | — | 1.70 ± 0.03 | 3.05 ± 0.05 | 2.15 ± 0.04 |
| <i>IIla</i> | 1.00 ± 0.03^a | 4.20 ± 0.05 | 0.60 ± 0.02 | — |
| <i>IIlb</i> | 0.75 ± 0.02^b | 4.20 ± 0.05 | 0.60 ± 0.02 | — |
| <i>IIlc</i> | 0.90 ± 0.03^c | 4.15 ± 0.05 | 0.60 ± 0.02 | — |
| <i>IIld</i> | $0.55 \pm 0.10^{d,g}$ | 4.15 ± 0.05 | 0.55 ± 0.10^g | — |
| <i>IIle</i> | — | 4.10 ± 0.05 | 0.66 ± 0.02 | — |
| <i>VI</i> | 0.32 ± 0.02^e | — | 0.32 ± 0.02^f | — |
| <i>VII</i> | 0.64 ± 0.04^e | — | 0.32 ± 0.02^f | — |

Splitting constant of: ^a three protons of the methyl group. ^b β -proton of the isopropyl group. ^c two β -protons of the butyl group. ^d β -proton of the sec-butyl group. ^e six equivalent protons of two methyl groups in positions 2 and 2'. ^f two equivalent protons in positions 5 and 5'. ^g Insufficient resolution of the spectrum does not allow to determine the splitting constants with more accuracy.

ducts of 2-methylhydroquinone (in which hydrogen peroxide is formed as a by-product) only in a small amount detectable by thin layer chromatography. Taking into account that the mixture of products yielded by the oxidation of 2-methylhydroquinone contains, in comparison with the mixture produced by the oxidation of biphenylhexol, further products which have not been identified more closely, it cannot be excluded that in the oxidation of 2-methylhydroquinone there participate still some other reactions of a non-radical character.

One of the reactions which may occur in the oxidation transformation of 2-methylhydroquinone in a concentrated aqueous solution of potassium hydroxide could be an addition of another hydroxyl group into the ring, similarly as has observed Corbett⁴ during the oxidation of 2-hydroxy-6-methylhydroquinone in dilute alkaline solutions. To investigate this possibility, we prepared isomeric tetrahydroxytoluenes *X* and *XI*. An attempt to obtain 2,3,5,6-tetrahydroxytoluene *XI* by Thiele's acetylation of 2-hydroxy-5-methyl-1,4-benzoquinone led to the formation of a tetraacetoxy derivative of 2,3,4,6-tetrahydroxytoluene *XII*. It was not quite clear from the original work⁶ which of the two isomers — *XI* or *XII* — arose in this reaction. Isomer *XI* was obtained by a more complex procedure described by Fichter⁷.

We recorded the EPR spectra of radicals formed by the oxidation of tetrahydroxytoluenes or the corresponding tetraacetoxytoluenes *X* ($a_{Me}^H = 3.50$ G, $a_2^H = 2.30$ G) *XI* ($a_{Me}^H = 1.30$ G, $a_4^H = 0.80$ G) and *XII* ($a_{Me}^H = a_5^H = 0.52$ G). We were not able to detect any analogous radicals in the reaction mixture obtained by the oxidation of 2-methylhydroquinone. It is therefore possible to exclude the formation of tetrahydroxytoluenes and the corresponding quinones in the mechanism of oxidation of 2-methylhydroquinone carried out under the conditions used here.

TABLE II
Calculated Spin Densities^a

| $k_{C_1-C_1'}$ ^b | θ | Radical VI | | Radical VII | |
|-----------------------------|----------|---------------|---------------|---------------|---------------|
| | | $\rho_{2,2'}$ | $\rho_{5,5'}$ | $\rho_{2,2'}$ | $\rho_{5,5'}$ |
| 1.0 | 0° | -0.0354 | -0.0260 | 0.2008 | -0.0159 |
| 0.9 | 26° | -0.0326 | -0.0252 | 0.1896 | -0.0168 |
| 0.8 | 36° | -0.0286 | -0.0244 | 0.1772 | -0.0175 |
| 0.7 | 45° | -0.0233 | -0.0237 | 0.1638 | -0.0182 |
| 0.6 | 53° | -0.0166 | -0.0231 | 0.1493 | -0.0187 |
| 0.5 | 60° | -0.0085 | -0.0225 | 0.1339 | -0.0192 |

^a Spin densities were calculated by McLachlan's method using parameters h_O 2.10 and k_{C-O} 1.85 for the oxygen atom, the inductive model with parameters $h_{C_2} = h_{C_2'} = -0.135$ for the methyl group and the usual values of parameter λ 1.2. ^b Resonance integral of the $C_{(1)}-C_{(1')}$ bond was varied according to the relationship $k_{C_1-C_1'} = \beta_0 \cos \theta$ where θ is the angle between the planes of aromatic rings in the radicals.

EXPERIMENTAL

Chemicals. 2-Methylhydroquinone, m.p. 123.5–124°C, 2-isopropylhydroquinone, m.p. 129.5–131°C, 2-n-butylhydroquinone, m.p. 88–88.5°C, 2-sec-butylhydroquinone, m.p. 100 to 101°C. 2-Hydroxy-6-methylhydroquinone was prepared by means of the reduction of an ether solution of 2-hydroxy-6-methyl-1,4-benzoquinone⁸ by shaking it with saturated aqueous solution of sodium hydrosulphite, m.p. 144°C (ref.⁴ 148°C). 2,3,4,5-Tetrahydroxytoluene was prepared in a small amount (only for measuring the EPR spectra of its oxidation products) by hydrolysis and reduction of 2-methyl-5,6-dimethoxy-1,4-benzoquinone⁹ with hydroiodic acid; 2,3,5,6-tetrahydroxytoluene was also obtained in a small amount only by reduction of 2-methyl-3,6-dihydroxy-1,4-benzoquinone⁷ with sodium hydrosulphite. 2,3,4,6-Tetraacetoxytoluene was prepared from 2-hydroxy-5-methyl-1,4-benzoquinone¹⁰ by Thiele's acetylation, m.p. 133–135°C (ref.⁶ 132–133°C).

2,2'-Dimethylbiphenyl-3,3',4,4',6,6'-hexol: A solution of 400 mg of 2,2'-bis(3-methyl-5-hydroxy-1,4-benzoquinone)⁸ in 50 ml of ether was shaken with 15 ml of saturated aqueous solution of sodium hydrosulphite until discolouration of the reaction mixture. The water layer was then shaken ten times with 30 ml of ether each time (the biphenylhexol formed is very well soluble in water). The joined ether extracts were shaken with 10 ml of water, dried with anhydrous magnesium sulphate and concentrated; the isolated solid substance was purified by crystallization from the mixture chloroform–acetone–hexane. The yield was 200 mg of crystals, m.p. 130–132°C. The results of elemental analysis showed that the substance obtained was a monohydrate of the compound required. After drying at 110°C/10 Torr for ten hours, an anhydrous substance was obtained, m.p. 203° with decomposition. For $C_{14}H_{14}O_6$ (278.3) calculated: 60.43% C, 5.07% H; found: 60.51% C; 5.15% H.

Chromatographic analysis of the reaction mixtures. For the chromatographic analysis of the reaction mixtures obtained by the oxidation of 2-isopropyl-, 2-butyl- and 2-sec-butylhydroquinone we used ascending paper chromatography on impregnated paper Whatman No 1. The systems most appropriate for this purpose were 20% formamide (impregnation)/benzene and 30% ethylene glycol (impregnation)/hexane–ether–pyridine¹ (3 : 2 : 0.2). For analyses of more polar reaction mixtures obtained by the oxidation of 2-methylhydroquinone or biphenylhexol, chromatography on thin layers of Silufol UV-254 (Kavalier) in the system acetone–hexane 3 : 2 proved to be more suitable.

EPR spectrometry. The measurement method, EPR spectrometer and the method of analysis of spectra have been described earlier². A flow arrangement was used for measuring spectra of primary radicals; a solution of hydroquinone under study was mixed with a solution of potassium hydroxide in close vicinity of the measuring cavity. Air oxygen dissolved in water or in 75% aqueous methanol at normal pressure and room temperature was used as the oxidizing agent. Concentrations of the components were chosen so that the resulting reaction mixture was a 0.005M solution of hydroquinone in 20% aqueous KOH. A constant flow rate (1–5 ml/min; always adjusted so as to achieve the best record of the spectrum) and a constant mixing ratio were maintained by means of a peristaltic pump. The spectra of secondary radicals were recorded after the flow of the reaction mixture through the cavity had been stopped, or in a stationary arrangement at the same concentrations.

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