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THE CATALYTIC OXIDATION OF 4-ARYLOXYPHENOLS

W. J. Mijs, O. E. van Lohuizen, J. Bussink and L. Vollbracht
Central Research Institute of AKU (Algemene Kunstzijde Unie N.V.)
and affiliated Companies, Arnhem, The Netherlands

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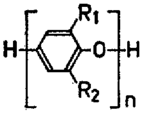
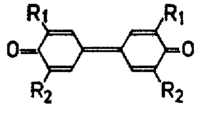
Abstract—The mechanism of the Cu^+/amine catalysed oxidation of a number of substituted 4-aryloxyphenols (dimeric phenols) has been studied by analysis of primary reaction products. Quinone ketals are postulated as intermediates which can decompose in two ways, depending on the substitution pattern of the starting 4-aryloxyphenol: a homolytic fission mechanism (two dimeric phenols yielding monomer and trimer as primary products), or an intramolecular rearrangement mechanism (two dimeric molecules giving a tetramer as a primary product). The tetramers are not formed by direct coupling of 4-aryloxyradicals, the oxygen of one radical attacking the *para* position of the terminal ring of the other. Experimental evidence is presented for the mechanisms proposed.

INTRODUCTION

Oxidation of 2,6-disubstituted phenols with oxygen, catalysed by amine and a copper I salt, can either afford high mol wt polyphenylene ethers (I) or substituted diphenoquinones (II).[1a-e] It is highly probable that the reaction proceeds through radical intermediates, since it can be initiated by several types of one electron transfer agents.[2-4] Accordingly, the initiation reaction is the formation of monomeric phenoxyradicals, which can give either C—O or C—C coupled dimeric products as a first step. It has also been found that dimeric 2,6-dimethylphenol [4-(2,6-dimethylphenoxy)2,6-dimethylphenol] as well as low polymers can be oxidatively polymerized to form high polymers of identical structure (I).[1c] Three suggested mechanisms for these polymerization reactions have been described recently:[1e]



I



II

1. End linking of polymer radicals, the oxygen atom of one polymeric aryloxyradical attacking the *para*-position of the terminal ring of the other ("uncoupled

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[1a] A. S. Hay, H. S. Blanchard, G. F. Endres and J. W. Eustance, *J. Am. Chem. Soc.* **81**, 6335 (1959); [b] A. S. Hay, *J. Polymer Sci.* **58**, 581 (1962); [c] G. F. Endres and J. Kwiatek, *Ibid.* **58**, 593 (1962); [d] G. F. Endres, A. S. Hay and J. W. Eustance, *J. Org. Chem.* **28**, 1300 (1963); [e] G. D. Cooper, H. S. Blanchard, G. F. Endres and H. Finkbeiner, *J. Am. Chem. Soc.* **87**, 3998 (1965).

[2] A. S. Hay, *Am. Chem. Soc., Div. of Polymer Chem.* Preprint booklet **2**, 319, Sept. (1961).

[3] C. G. Haynes, A. H. Turner and W. A. Waters, *J. Chem. Soc.* 2823 (1956).

[4] B. O. Lindgren, *Act. Chem. Scand.* **14**, 1203 (1960).

electron"[5] or "phenonium ion" mechanism[6]). The postulated odd-electron transfer through the ether linkages of a polymer chain to the *para*-position of the terminal ring is, however, not easy to understand. Even in a dimer, this odd-electron transfer is improbable, as has been pointed out[7] on the basis of ESR measurements on a number of 4-substituted 2,6-di-t-butylphenols and their sulphur analogs. A substitution mechanism, on the other hand, seems unlikely, since compounds such as 2,6-dimethylanisole and the corresponding dimer do not act as terminating agents for the polymerization and accordingly could be recovered unchanged.[5]

2. "Quinone ketal rearrangement"[5] is dealt with more elaborately below. This mechanism was originally termed "quinol ether rearrangement", but since the intermediates involved are actually quinone ketals, the designations "quinone ketal rearrangement" and "quinone ketal equilibration" are used throughout this paper.

3. "Quinone ketal equilibration"[1e] or "redistribution"[8] mechanism. Direct evidence for this mechanism has been provided[1e] by identification of the primary products from the oxidation of 2,6-dimethylphenol dimer, isolated by GLC of the trimethylsilyl derivatives. Similar results had been obtained independently using TLC.[8]

In this paper we present evidence for quinone ketal and quinol ether intermediates (Scheme 1, V and IV, respectively) and their reactions (paths C, D, and E) by analysis of the primary products from oxidation of 4-aryloxyphenols (III^{a-f}) (Table 1).

RESULTS

The structure of oligomeric phenols formed by partly oxidizing the 4-aryloxyphenols (III^{a-f}) with oxygen (15–50% of the theoretical amount) and cuprous chloride–N,N-tetraethylethylenediamine as catalyst at various temperatures has been analysed.

With 2,6-dimethylphenol dimer (III^a) the first main reaction products at 40° were monomer $VIII^a$ and trimer IX^a; a series of higher oligomers was also formed as the reaction proceeded. From phenol dimer (III^b) again at 40° the "para-*tetramer*" VI^b was isolated as the main product, together with smaller amounts of the corresponding "para-*hexamer*" VII^b and the "ortho-*tetramer*" X^b. The hexamer VII^b was also isolated from oxidation of trimer IX^b. No monomer ($VIII^b$) or trimer (IX^b) was found in the reaction mixture from the oxidation of III^b. TLC also showed that the corresponding pentamer was absent. (Experimental). At 80°, however, monomer, trimer and probably pentamer were detected among the minor products, although tetramer VI^b and hexamer VII^b were still the major products. This was also the case when the amine component of the catalyst was increased in the reaction at 40°. Generally the amount of rearrangement or homolytic fission reaction occurring seemed to be dependent on subtle reaction conditions e.g. concentration of catalyst components, solvent and temperature.

From III^c and from III^d *tetramers* VI^c and VI^d, respectively, were isolated as major products (reaction temp 5°). Neither trimers (IX^c and IX^d) nor monomers

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[5] H. L. Finkbeiner, G. F. Endres, H. S. Blanchard and J. W. Eustance, *Am. Chem. Soc., Div. of Polymer Chem.* Preprint booklet **2**, 340 Sept. (1961).

[6] W. A. Butte and C. C. Price, *J. Am. Chem. Soc.* **84**, 3567 (1962).

[7] K. Scheffler, *Z. Elektrochem.* **65**, 439 (1961).

[8] J. Bussink, O. E. van Lohuizen, J. L. Mulder and L. Vollbracht, unpublished. (cf. le. Footnote 8). After completion of the Ms, the work of E. Mc. Nelis, *J. Org. Chem.* **31**, 1255 (1966), describing the oxidative coupling of 2,6-dimethylphenol with MnO_2 according to the redistribution mechanism, came to our attention.

Scheme 1. Oxidation of 4-aryloxyphenols

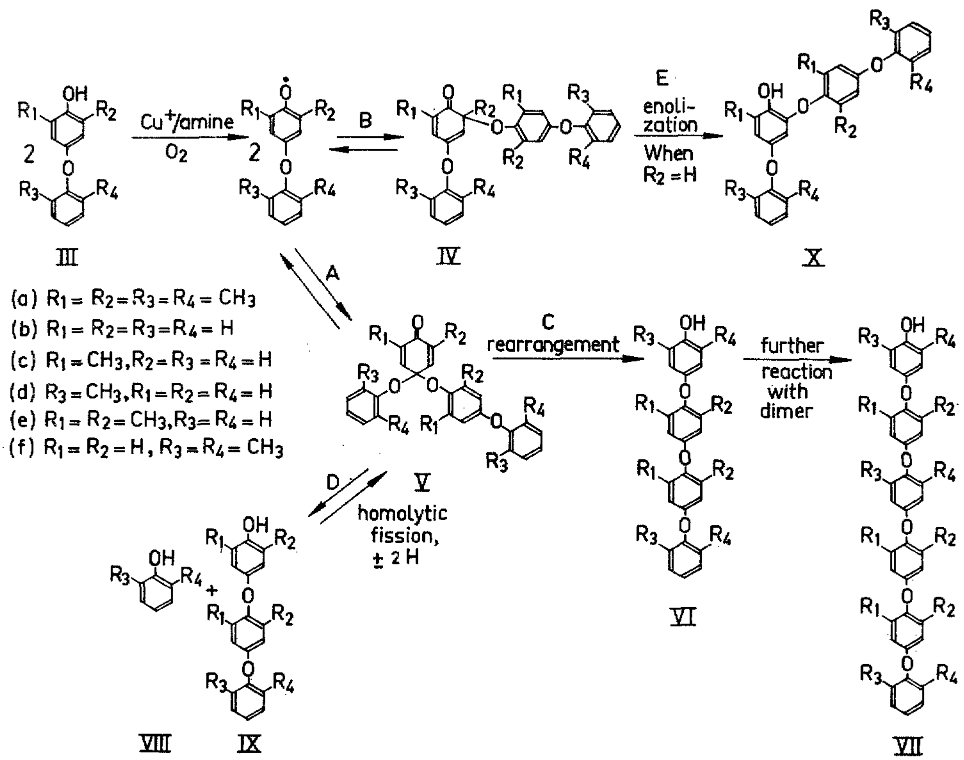


TABLE 1. PRIMARY REACTION PRODUCTS AND REACTION PATH FROM OXIDATION OF 4-ARYLOXYPHENOLS

Starting 4-aryloxyphenol	Main primary products	Main reaction path
III^{a}	VIII^{a} IX^{a}*	A–D*
III^{b}	VI^{b} X^{b}*	A–C B–E*
III^{c}	VI^{c}†	A–C†
III^{d}	III^{d}†	A–C†
III^{e}	VIII^{e} IX^{e}*	A–D*
III^{f}	VIII^{f} IX^{f}*	A–D*

* At 40° † At 5°.

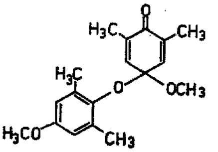
(VIII^{c} and VIII^{d}) could be detected under the conditions used, but again these compounds appeared among the reaction products at higher temperatures (20–40°). No attempt was made to isolate "*ortho*-tetramers" (corresponding to X) which were present only in small amounts as evidenced by TLC.

In another experiment, III^{e} and III^{f} were oxidized at 40° yielding monomers VIII^{e} and VIII^{f} and trimers IX^{e} and IX^{f}. The latter two were not isolated, but their presence was indicated on thin layers. Phenolic oligomers higher than hexamer were formed in small amounts in all cases, but these were not isolated. In all the oxidations minor amounts of other compounds essentially different from the series of oligomers discussed above were detected among the reaction products (TLC). Presumably these are C—C coupled oligomers having two OH groups per molecule.

DISCUSSION

From the results described above, it can be concluded, that quinone ketals and quinol ethers are intermediates in the oxidation of 4-aryloxyphenols. Whether they must be formulated as real chemical entities in this particular case, which possibly can be isolated at lower temperatures, or just as transition states, is an unanswered question at the moment.

The formation of quinone ketals by oxidation of hindered phenols has been reported earlier in the Lit.,[8–13] and there is also some evidence for their homolytic decomposition.[8,11,12,13]. The isolation of the quinone ketal XII from the oxidation of


(XII)

2,6-dimethyl-4-methoxyphenol[9] is of particular interest. Owing to the delocalization of the free electron in the phenoxy-radical the quinol ether IV or the quinone ketal V may result from the phenoxyradicals derived from III^{a-f}. Quinol esters of structures analogous to IV have been prepared.[14] The enolization (E), leading to "*ortho*"-tetramers X can only take place, however, if $R_2 = H$.

The quinone ketals V, depending on substitution pattern, catalyst and reaction-temperature, would rearrange to "*para*"-tetramers VI (path C) or decompose homolytically to yield monomers VIII and trimers IX (path D). Generally only even-numbered oligomers are formed in the reactions of dimers III along path A–C; while both *even* and *odd* numbered oligomers result from reaction path A–D.

The same tetramer VI could be formed by intramolecular rearrangement (C) or by intermolecular reaction of monomer and trimer (via path D). No precise quantitative measurements have been carried out to ascertain the extent of rearrangement in addition to homolytic decomposition of quinone ketals V^a, V^e and V^f.

With the unsubstituted quinone ketal V^b, rearrangement C occurs exclusively at temperatures below 70°, while at higher temperatures homolytic decomposition resulting in the formation of monomer VIII^b and trimer IX^b becomes apparent. Although, with the alkyl-monosubstituted quinone ketals (V^c and V^d), the latter mechanism starts to play a role at room temperature. Clearly, the stability towards homolytic decomposition of the substituted quinone ketals V^a, V^e and V^f and to a less extent V^c and V^d, is reduced compared with the unsubstituted V^b. This is presumably due to steric and inductive effects of the substituents. This is compatible with studies[13] on the redistribution reaction of several 4-aryloxyphenols including III^a and III^b, using 2,4,6-tri-t-butylphenoxy (TTBP) as the oxidizing agent. The stability of the key intermediate in this reaction, the quinol-ether formed by C—O coupling of the aryloxyradical with TTBP at the *para* position, was also found to decrease with alkyl substitution in the penolic nucleus. This contributed to the ease of redistribution.

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[9] C. Martius and H. Eilingsfeld, *Liebigs Ann.* **607**, 159 (1957).

[10] E. Müller, K. Ley and G. Schlechte, *Chem. Ber.* **90**, 2660 (1957).

[11] E. Müller, A. Rieker and A. Schick, *Liebigs Ann.* **673**, 40 (1963).

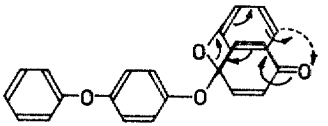
[12] H. D. Becker, *J. Org. Chem.* **29**, 3068 (1964).

[13] D. A. Bolon, *A.C.S. Polymer Div.* Preprints 7 (1), 173 (1966).

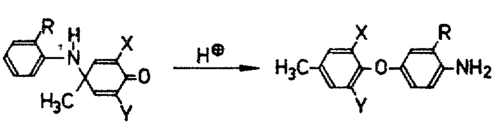
[14] E. Zbiral, O. Saiko and F. Wessely, *Mh. Chem.* **95**, 512 (1964).

Tetramers VI^b, VI^c and VI^d and a hexamer (VII^b formed presumably by reaction of tetramer VI^b and dimer III^b) were isolated under conditions, where strictly no monomers or trimers could be detected in the reaction mixture. Monomer does not react further very rapidly once it has been formed, as was proved by addition of the appropriate monomers during the polymerization. *The location of the methylgroups in the aromatic nuclei in* VI^c *and* VI^d *supports the rearrangement mechanism* (C) *but rules out the uncoupled electron or phenomium ion mechanism, containing direct coupling of dimeric phenoxyradicals.*

It can be assumed, that this also holds for the oxidation of unsubstituted 4-phenoxyphenol, although naturally no direct proof can be given, since the aromatic nuclei in the tetramer VI^b are not "marked" by Me-groups, allowing determination of their sequence, as in VI^c and VI^d. We are, therefore, left with the possibilities of a very rapid intermolecular reaction between monomeric and trimeric phenoxyradicals, resulting from the quinone ketals V, in a solvent cage or the related possibility of the intramolecular rearrangement (C). The latter presumably takes place by a series of electron displacements involving concerted homolytic breaking of the ketal C—O bond and formation of the new —O bond as depicted below.



The exclusive formation of two tetramers VI^b and X^b as major oxidation products of III^b can be accounted for by coupling of dimeric radicals via V^b and IV^b respectively. Except for very minor amounts, all other oxidation-products of III^b were identified quantitatively and no specific coupling products of monomer and trimer radicals were detected, as would be expected from reaction of these species in a solvent cage. Moreover the extensive homolytic decomposition of V^e suggests that the lifetime of the unsubstituted phenoxyradical is sufficient to allow diffusion away from the solvent cage. For these reasons, the quinone ketal rearrangement is preferable. An analogy in some respects exists in the intramolecular rearrangement of *para*-quinamines to 4-aminobiphenyl ethers, described recently.[15]



R = H, alkyl ; X = Br, alkyl ; Y = Br, alkyl

In this rearrangement steric conditions appear also to be favourable for a transition state in which the *para* position of the aromatic ring is close to the carbonyl oxygen of the quinonoid ring. It can be assumed that oxidative polymerization of phenols generally follow the mechanisms outlined in Scheme 1.

With 2,6-dimethylphenol the Cu/amine catalysed oxidation leads exclusively to

[15] B. Miller, *J. Am. Chem. Soc.* **86**, 1127, 1135 (1964).

1,4-polyphenylene ethers[1,b,c,e] presumably because the enolization E is impossible here and back formation (B) if the dimer results ultimately in exclusive reaction along A–D or, theoretically, A–C.

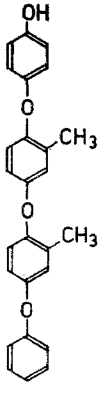
The "uncoupled electron" mechanism being rejected, other minor coupling reactions occurring in the final stage of the polymerization might explain the steep polycondensation-type rise[1e] of degree of polymerization towards the end of the reaction.

Structure analyses of oligomeric phenols

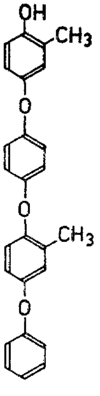
All reactions of 4-aryloxyphenols III^{a-f} have been followed by TLC using systems which allowed clear separation of "*para*"-oligomers (type III, VI, VII and IX), "*ortho*"-oligomers (type X) and most C—C coupled products with two OH groups per molecule. Compounds III, VI, VII, VIII and IX could be most clearly distinguished from each other by using two-dimensional TLC. A number of model compounds were used as references (Experimental).

All monomers VIII, trimers IXa and IXb and tetramer VIb were identified by comparison with authentic samples, often obtained by independent syntheses.

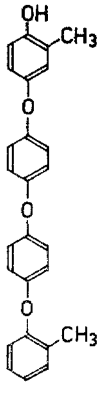
GLC, in addition to TLC, proved to be particularly useful in the detection of the monomers. The structure of the hexamer VIIb was established by mass, IR and NMR spectroscopy. A clear analogy of the IR and NMR spectra with those of tetramer VIb was apparent. Hydroxy group, aromatic ether, 1,4- and mono-substituted benzene rings were easily recognized in the IR. The NMR spectrum of VIIb showed in addition to one single signal in the aromatic region, attributable to equivalent protons from the middle rings, a small concentration dependent signal from the OH-proton. The mass spectrum provided the mol. wt, but it was very difficult to observe any fragmentation pattern. In order to prove the quinone ketal rearrangement mechanism, it was necessary to distinguish clearly between tetramers VIc and XIII as well as between VId and XIV. This was accomplished on the basis of the following arguments:



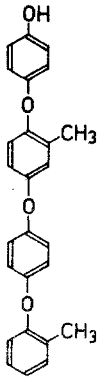
VI^{c}



XIII



VI^{d}



XIV

1. The mol. wt of VIc could be established by mass spectrometry, whereas VId decomposed (by "redistribution") in the spectrometer. The signal area of Me protons

and aromatic protons, however, were in accordance with tetrameric structures for VIc and VId, having two Me groups and four aromatic rings.

IR spectra of VIc and VId showed the expected structural features: aromatic ether, OH and Me; monosubstituted benzene ring for VIc (not for VId).

2. Tetramer VId moved slightly faster on thin layers than VIc, while IIIc (starting product for VIc) moved faster than IIId (starting product for VId). As a general rule with the system used, it was found that the oligomers with "phenol-heads" (such as IIId and VIc) always show the smaller R_f as compared with oligomers with "*o*-cresol-heads" (such as IIIc and VId). This is illustrated in Fig. 1, a number of reference compounds being included, e.g. oligomers with "2,6-xylenol heads" which move fastest.

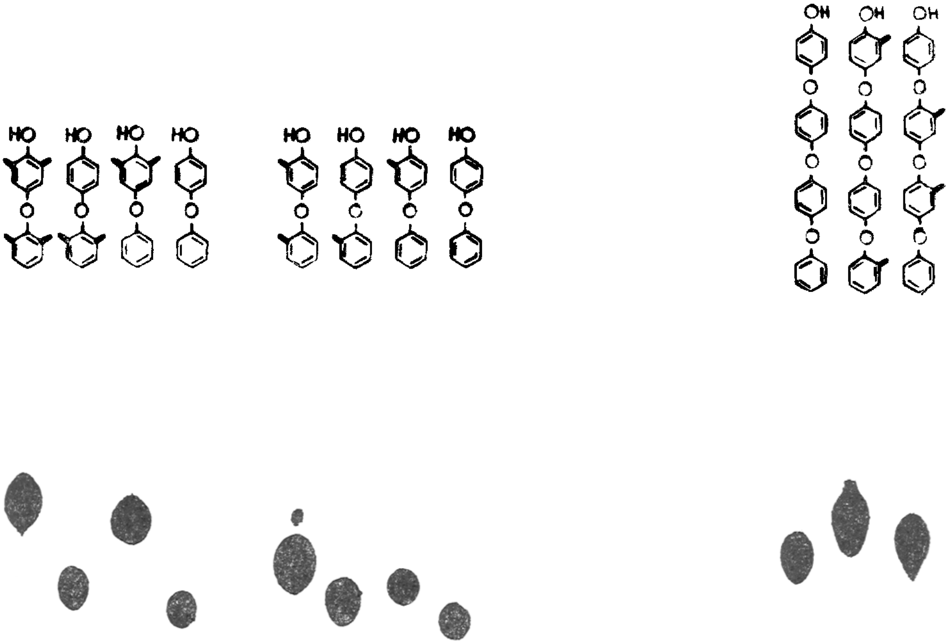


FIG. 1. Thin-layer chromatograms of phenolic dimers (III) and tetramers (VI). The R_f's are increasing in upward direction.

3. A comparison of NMR spectra* of VIc and VId, showed that the OH-proton of VId was always at higher field than the OH-proton of VIc. This is illustrated in Fig. 2, which includes similar measurements on the starting products IIIc and IIId.

These results are in accordance with investigations[16,17] and are due to the lesser tendency of the OH in the *o*-cresol derivatives to form hydrogen bonds in apolar solvents, than the OH in phenol derivatives without *ortho*-substituents.

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* Over a suitable concentration range at room temp in CCl_4 soln.

[16] C. M. Huggins, G. C. Pimentel and J. N. Shoolery, *J. Phys. Chem.* **60**, 1311 (1956).

[17] B. G. Somers and H. S. Gutowsky, *J. Am. Chem. Soc.* **85**, 3065 (1963).

4. The Me protons in the NMR spectrum of VId showed different chemical shifts, as was to be expected from their unequivalent positions. With VIc, however, the Me protons were found in very nearly the same position. Resolution was only just sufficient to observe a doublet (separation 0·5 c/s). Another oxidation product from IIId, most probably a hexamer, showed the two Me proton signals clearly separated (as with VId) with area ratios 1:2. No monosubstituted benzene rings were present in the IR spectrum. These facts are in accordance with structure VIId.

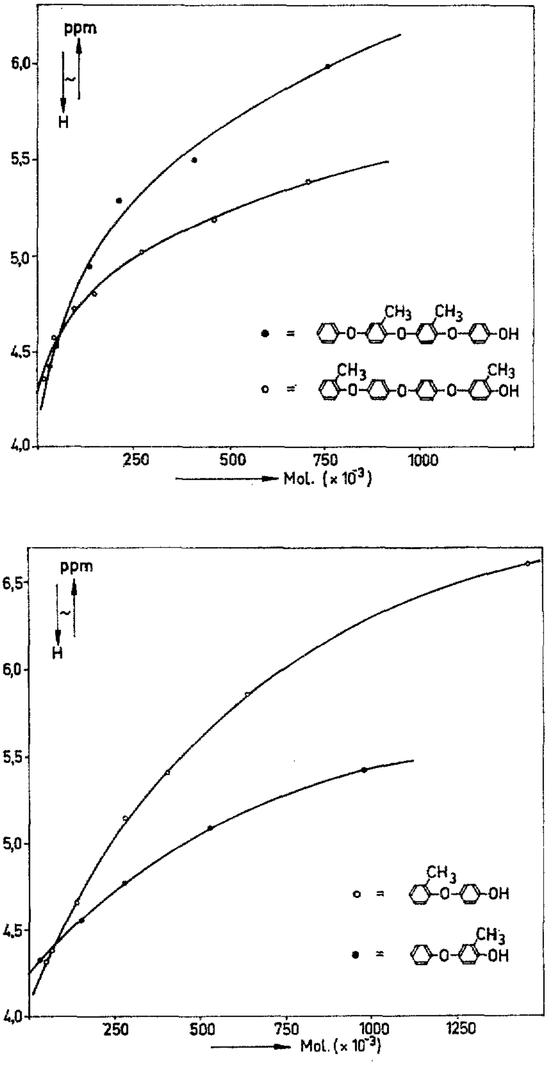

FIG. 2. The position of the OH-proton as a function of concentration in the NMR spectra of IIIc, IIId, VIc and VId.

5. Mild bromination, shown to occur exclusively at the *ortho* positions with respect to the OH group with model compound VIb, afforded a monobromo derivative from VId and a dibromo derivative from VIc.

EXPERIMENTAL

Physical methods and analyses. IR measurements were performed on a Perkin–Elmer 221 grating prism spectrometer. NMR measurements were carried out on a Varian A-60 spectrometer. Solns in CCl_4 were used with TMS added as a reference, unless otherwise stated. Mol. wt determinations were made on a Mechrolab vapour pressure osmometer unless otherwise stated. Elementary analyses were done by Mr. G. Hesse of our laboratory and Mr. W. M. Hazenberg (University of Groningen).

Polymerization reactions

General procedure. The reactions were carried out in a double-walled closed vessel with a pumping thermostat for temp control and a gas burette for measurements of O uptake. All aryloxyphenols (III), other reagents and the solvents used were purified by crystallization or distillation.

To a soln of N,N-tetraethylethylenediamine (0·12–0·25 mmole) in toluene (25–50 ml) were added cuprous chloride (0·25–0·50 mmole) anhyd $MgSO_4$ (15–30 mmole) as drying agent and the 4-aryloxyphenol (10–20 mmole). The reaction mixture was stirred vigorously to ensure satisfactory diffusion of the O kept under atm press. After 15–50% of the theoretical amount of O had been consumed, 5 volumes of a MeOH–conc HCl mixture were added to stop the reaction and to precipitate any high polymer formed. The ppt was filtered off, the catalyst removed by water extraction, and the solvent evaporated. From the residue the reaction products were isolated as described below.

Isolation of oligomers (VI–X). In general no attempt was made to isolate reaction products quantitatively. A quantitative evaluation of the oxidation products of IIIb, enabling identification of all but the very minor products was carried out, using GLC of the trimethylsilyl ethers[1e,18] in combination with TLC. In a 15% oxidation mixture (20% by wt conversion, unchanged dimer removed by high vacuum mol. distillation), the products were: "*para*"-tetramer (VIb, 12·5 wt%), "*ortho*"-tetramer (Xb, 2·7 wt%), C–C coupled products, moving slower on TLC (1·2 wt%) and the major part of the remaining material proved to be VIIb (from TLC, 3·6 wt%). Neither monomer VIIIb nor trimer IXb was found to be present. Trimethylsilyl ethers of authentic samples (see below) of VIb, VIIIb, IXb and Xb were used for GLC identification and quantitative evaluation.

For qualitative identification purposes the isolation of VIb, VIIIb and Xb was carried out from a 50% oxidation mixture with higher conversion. This reaction mixture was redissolved in acetone (40 mg/ml) and the hexamer VIIb and part of the tetrameric material were precipitated by adding 3 vols of 33% aqueous acetone. Dimer IIIb remained in soln. The ppt was collected and the components separated by means of liquid chromatography, using silica in benzene as the stationary phase and benzene as the eluent. The "*ortho*"-tetramer appeared in the first fractions. From these fractions Xb could be isolated after repeated column chromatography. VIIb was isolated from the benzene column fractions by concentration and cooling and crystallization from boiling MeOH. Tetramer VIb was obtained from the benzene mother liquor. An identical hexamer VIIb was obtained similarly from a 25% oxidation mixture of trimer IXb.

Tetramers VIc and VId were isolated from oxidations at 5° of IIIc and IIId, respectively. (O consumption 15% of the theoretical amount.) Molecular distillation (horizontal tube-type apparatus with cold finger at $-35°$) at $20–50°/10^{-5}$ mm and subsequently at $50–70°/10^{-5}$ mm (60–80 hr) eliminated the unchanged dimers. At $70–95°/10^{-5}$, the bulk of tetramer was distilled (40–60 hr) together with some "*ortho*"-tetramer (type X). Further distillation resulted in isolation of small amounts of a hexamer (presumably VIId) of which an NMR spectrum could be obtained. Final purification was achieved by liquid column chromatography, as described above. As a minor product from the oxidation of IIIc, a C—C coupled tetramer most probably 2,2′-dihydroxy-3,3′-dimethyl-5,5′-diphenoxybiphenyl was obtained. Both tetramers VIc and VId were colourless oils.

Analytical data of reaction products

Compound VIIb *from* IIIb. M.p. 194–195°. Mol. wt (from mass spectrum): 554. IR spectrum (KBr disc): 3100, 3065, 3045 (CH stretching), 1880 (combination tone from CH bendings 1,4-substituted aromatic ring) 1590, 1490 (benzene ring) 1360 (OH bending) 1225 (C—O stretching) 1100, 1010 (CH in plane bending 1,4-substituted aromatic ring) 860, 850, 830 (CH out of plane bending 1,4-substituted aromatic ring) 750, 685 cm^{-1} (monosubstituted aromatic ring). NMR

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[18] This technique seems to be only reliable for quantitative purposes with the oxidation of IIIb, since with substituted oligomers, the silylation procedure caused slight redistribution.

spectrum (in $AsCl_3$): multiplet with a strong single peak at 7·15 ppm (total aromatic proton area 25 protons), 530 ppm (OH, concentration and temp dependent, one proton). (Found: C, 77·71; H, 4·53. $C_{36}H_{26}O_6$ requires: C, 77·96; H, 4·73%.)

Compound VIIb *from* IXb. M.p. 193–194°. Mixed m.ps with the product from IIIb gave no depression. NMR and IR spectra were also identical.

Compound Xb. M.p. 76–77°. IR spectrum (CS_2 soln): 3550 (internally associated OH), 3065, 3045 (CH stretching) 1350 (OH bending), 1210 (C—O stretching) 970 (CH in plane bending 1,2,4-substituted aromatic ring) 745, 680 cm^{-1}. (CH out of plane bending monosubstituted aromatic ring.) (Found: C, 77·61; H, 5·10. $C_{24}H_{18}O_4$ requires: C, 77·82; H, 4·90%.)

Compound VIb. M.p. 143–144°. Mixed m.ps with the synthetic sample (see below) gave no depression. IR and NMR spectra of both compounds were also identical.

Compound VIc. IR spectrum (CCl_4 soln): 3610 (OH stretching with broad intermolecularly associated OH) 3060, 3045, 2960, 2930, 2850, 2738 (CH stretching) 1590, 1485 (aromatic rings) 1378 (Me bending) 1335 (OH bending) 1215 (C—O stretching) 950 (CH in plane bending 1,2,4-substituted rings) 686 cm^{-1} (monosubstituted aromatic ring). NMR spectrum: multiplet in the aromatic region 6·7–7·3 ppm (15 protons), 5·05 ppm (OH, concentration and temp dependent, one proton) 2·25 ppm (Me, two signals 0·5 c/s apart in the expanded spectrum, total area: 6 protons). Mol. wt, from mass spectrum: 398; calc: 398. (Found: C, 77·86; H, 5·47. $C_{26}H_{22}O_4$ requires: C, 78·37; H, 5·57%.)

Compound VId. IR spectrum (CCl_4 soln): 3610 (OH stretching with broad intermolecularly associated OH) 3060, 3040, 2960, 2930, 2856, 2743 (CH stretching) 1585, 1475 (aromatic rings) 1380 (Me bending) 1330 (OH bending) 1204 (C—O stretching) and 954 cm^{-1} (CH in plane bending 1,2,4-substituted aromatic rings). No absorption for monosubstituted aromatic rings was detected. NMR spectrum: multiplet 6·65–7·30 ppm with a high single peak at 6·90 ppm (15 aromatic protons), 4·79 ppm (OH, conc and temp dependent, one proton) 2·20 and 2·26 ppm (Me signals, 3 protons each). (Found: C, 77·98; H, 5·42. $C_{26}H_{22}O_4$ requires: C, 78·37; H, 5·57%.)

Bromination experiments

Tetramers (VIb, VIc and VId respectively, 45 mg in 5 ml chf) were bromated with Br in chf soln (0·1 M) using a 20% excess on the theoretical amount required for the introduction of two Br atoms per molecule. After dropwise addition of the Br soln, the reaction mixtures were allowed to stand at 20° for 6 hr and after working up the products were analysed for Br content. The IR spectrum of the bromination product of VIb (in CS_2) showed one single internally associated OH absorption at 3508 cm^{-1}, monosubstituted benzene ring absorption being undisturbed at 682, 745 cm^{-1}.

Dibromoderivative of VIb: (Found: Br, 30·90. $C_{24}H_{16}Br_2$ requires: Br, 30·26%.)

Dibromoderivative of VIc: (Found: Br, 28·31. $C_{26}H_{20}Br_2O_4$ requires: Br, 28·73%.)

Monobromoderivative of VId: (Found: Br, 17·16. $C_{26}H_{21}BrO_4$ requires: Br, 16·74%.)

Syntheses

4-(2,6-*Dimethylphenoxy*)2,6-*dimethylphenol* (IIIa). This compound was prepared as described[1c] by an Ullmann reaction of 2,6-dimethylphenol and 2,6-dimethyl-4-bromoanisole, yield 75%, m.p. 109–111° crystallized from light petroleum.

2-*Methyl*-4-*phenoxyphenol* (IIIc). 2-Methylanisole (44 g, 0·36 mole, prepared from *o*-cresol by reaction with methylsulfate in alkaline soln) was bromated[19] in AcOH soln (240 ml, 80%) to give a 68% yield of 2-methyl-4-bromoanisole (m.p. 71–73°). This compound (40·2 g, 0·2 mole), PhONa (0·2 mole, prepared from 4·69 g Na and 18·8 g phenol in MeOH) and cuprous chloride (1 g) was heated for 3 hr at 230°, as in the modified Ullmann procedure.[20] After cooling to room temp, conc HCl (20 ml) and water (60 ml) were added, the crude product was isolated by ether extraction and purified by distillation under reduced press, the fraction with b.p. 106–110°/0·25 mm being collected, yield of 2-methyl-4-phenoxyanisole: 60%. Hydrolysis of the Me ether was effected by refluxing (2 hr) in 57% HI in glacial AcOH to yield 76% of IIIc (b.p. 119–125°/0·22 mm). Overall yield of IIIc from 2-methylanisole: 31% (22·3 g).

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[19] A. N. Meldrum and M. S. Shah, *J. Chem. Soc.* **123**, 1982 (1923).

[20] G. Stamatoff, French patent 1,301,174 (1962) to E. I. du Pont de Nemours Company, Wilmington (Del.).

IR spectrum (CS_2 soln): 3590 (OH stretching with broad intermolecularly associated OH) 3065, 3045, 2950, 2925, 2856, 2739 (CH stretchings), 1587 (aromatic rings), 1373 (Me bending) 1321 (OH bending) 1220, 1190 (C—O stretching) 955 (CH in plane bending 1,2,4-substituted ring) 752, 685 cm^{-1} (CH out of plane bending monosubstituted ring). NMR spectrum: multiplet 6·50–7·20 ppm (8 aromatic protons), 4·73 ppm (OH, conc and temp dependent, one proton) 2·16 ppm (Me, 3 protons). (Found: C, 77·82; H, 6·00. $C_{13}H_{12}O_2$ requires: C, 77·98; H, 6·04%.)

4-(2-*Methylphenoxy*)*phenol* (IIId). This synthesis was carried out as for IIIc, from 4-bromoanisole (93·5 g, 0·5 mole) and sodium-*o*-cresolate (65 g, 0·5 mole), yield of 4-(2-methylphenoxy)-anisole 46 g (43%) b.p. 98–100°/0·17 mm. Hydrolysis of the Me ether was effected by refluxing 1·5 hr in HI–AcOH, yield 92%. Overall yield of IIId: 36% (43 g), m.p. 35–36°. IR spectrum (CS_2 soln): 3592 (OH stretching, with broad intermolecularly associated OH) 3070, 3028, 2950, 2927, 2850, 2735 (CH stretchings) 1582 (aromatic rings) 1378 (Me bending) 1328 (OH bending) 1235, 1210, 1175 (C—O stretching) 840, 825, 776 (CH out of plane bending). No monosubstituted nor 1,2,4-substituted rings were detected by IR. NMR spectrum: multiplet 6·55–7·15 ppm with a high single peak at 6·57 ppm (8 aromatic protons), 5·40 ppm (OH, conc and temp dependent, one proton) 2·20 ppm (Me, 3 protons). (Found: 77·81; H, 6·10. $C_{13}H_{12}O_2$ requires: C, 77·98; H, 6·04%.)

2-(4-*Phenoxyphenoxy*)4-*phenoxyphenol* (Xb). 4-Phenoxyphenol (46 g, 0·25 mole) was brominated at the 2-position with Br in CS_2 soln at 5°,[21] yield of 2-bromo-4-phenoxyphenol, b.p. 168°/2 mm: 63·6 g (96%). Refluxing with methyl sulfate in alkaline soln afforded 2-bromo-4-phenoxyanisole. This compound (51 g, 0·19 mole) was reacted with the Na salt of 4-phenoxyphenol (39·5 g, 0·19 mole) as described above for the prep of IIIc, yield 42 g (58%). After hydrolysis of the Me ether with HI in AcOH soln, the crude product was converted into the trimethylsilyl ether with trimethylsilyl chloride in pyridine. After distillation (b.p. 212–214°/2 mm) and subsequent hydrolysis of the trimethylsilyl ether, the product Xb was finally purified by crystallization from cyclohexane, yield of pure Xb: 29 g (33% overall) m.p. 72–74°. This synthetic product proved to be identical in all respects (mixed m.p., IR and NMR spectra) with the compound isolated from the oxidation of IIIb.

4-(4-*Phenoxyphenoxy*)*phenol* (IXb). This compound was prepared from 4-bromoanisole and the Na salt of 4-phenoxyphenol, followed by hydrolysis of the Me ether as described in the prep of IIIc, yield 38% m.p. 105–106°. IR spectrum (CS_2 soln): 3594 (OH stretching, with intermolecular association) 3060, 3040 (CH stretching), 1590 (aromatic rings) 1330 (OH bending) 1210, 1190 (C—O stretching) 1100, 1010 (CH in plane bending 1,4-substituted rings) 740, 686 cm^{-1} monosubstituted rings (CH out of plane bending). (Found: C, 77·68; H, 5·33. $C_{18}H_{14}O_3$ requires: C, 77·68; H, 5·07%.) Mol. wt, found: 274; Calc: 278·31.

Phenol tetramer (VIb). This compound was prepared from Na salt of 4-phenoxyphenol and 4-bromo-4′-methoxybiphenyl ether (prepared from 4-methoxybiphenyl ether by reaction with Br in CS_2 at 5° [22]) as described for IXb, overall yield 35%; m.p. 145–146°. IR spectrum (CH_2Cl_2 soln): 3583 (OH stretching with slight intermolecular association) 3065, 3036 (CH stretching) 1876 (combination tone from CH bending 1,4-substituted aromatic rings) 1580, 1480 (aromatic rings) 1330 (OH bending) 1100, 1010 (CH bending 1,4-substituted rings) 740, 685 cm^{-1} (monosubstituted ring; the latter maxima decrease in intensity in the series phenol dimer, trimer, tetramer, hexamer). NMR spectrum ($AsCl_3$ soln): multiplet 6·80–7·38 ppm with two high peaks at 7·06 and 7·09 ppm (17 aromatic protons) 4·02 (OH, conc and temp dependent, one proton). (Found: C, 77·49; H, 5·02. $C_{24}H_{18}O_4$ requires: C, 77·82; H, 4·90%.) Mol. wt, Found: 368; Calc: 370·41.

Thin-layer chromatography. TLC glass plates with 0·25 mm silica layers (gypsum as binder) were used throughout the experiments. CCl_4/MeOH (9:1) was used as the mobile phase in one dimension and CH_2Cl_2 in the second dimension. Runs were made in a vapour-saturated chamber. Detections were by phosphomolybdic acid (0·15 g/ml in MeOH, general reagent) or by 2,6-dibromoquinonechloroimide (0·005 g/ml in MeOH, specific reagent, for phenols). All polymerizations were followed by two-dimensional TLC. This technique was particularly successful in achieving satisfactory separation of the phenol oligomers within the "*para*" series (dimers III, trimers IX, tetramers VI etc.) and the corresponding monomers, formed on oxidation of IIIa, IIIb, IIIc and IIId, respectively, under the various reaction conditions described above. Higher oligomers were moving faster than the lower ones within each "*para*" series. Separation of VIc and IIIc proved to be difficult, but just possible, since VIc is a tetramer with "phenol head" (moving relatively slower) and IIIc a dimer with

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[21] D. E. Janssen, J. Van Allan and C. V. Wilson, *J. Org. Chem.* 20, 1326 (1955).

[22] R. Adams and C. S. Marvel, *Organic Syntheses* Coll. Vol. I; 123 (1932).

"cresol head" (moving relatively faster). The absence, or presence of various monomers VIII, of trimers IXa and IXb and of tetramer VIb in the oxidation mixtures of the corresponding dimers III at different reaction temps was demonstrated, using the authentic samples as references.[23] The absence of "*para*"-pentamer and, again, of trimer IXb in the oxidation reaction mixture of IIIb was demonstrated by comparison of this oligomer series with that formed on oxidation of a 1:1 mixture of IIIb and IXb. TLC of the latter reaction mixture clearly showed the presence of trimer and pentamer, which were completely absent in the former. A number of model compounds were also used as references in this study (e.g. 4-phenoxyphenol, 2-phenoxyphenol, 4,4′-dihydroxybiphenyl and 2,2′-dihydroxybiphenyl).

Groups of "*ortho*"-oligomers (corresponding to X), the above-mentioned "*para*"-oligomers and most C—C coupled products were easily recognized and separated in one dimension, using these model references. "*ortho*" C—C coupled oligomers (2,2′-dihydroxybiphenyl derivatives) generally moved faster than "*para*"-C—C coupled products (4,4′-dihydroxybiphenyl derivs). For instance, tetramer VIc was contaminated with small amounts of a C—C coupled product, believed to be 2,2′-dihydroxy-3,3′-dimethyl-5,5′-diphenoxybiphenyl from IR and NMR. But satisfactory detection and isolation was achieved by the techniques described above.

Gas liquid chromatography (*GLC*). An F. and M. model 810 gas chromatograph was used with 20% of a 1:1 mixture of Apiezon L and lanoline on chromosorb W (45–60 mesh) as column material. Temps around 130° were used. Detection was by flame ionization. With GLC, in addition to TLC, monomers VIIIa, VIIIe and VIIIf in the appropriate reaction mixtures were detected by their retention times, in comparison with the authentic samples. The absence of VIIIb, VIIIc and VIIId in the reaction mixtures from oxidations of IIIb, IIIc and IIId, respectively, was also verified by GLC.

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[23] A sample of trimer IXa[1c] was kindly supplied to us by Dr. J. R. Elliott, General Electric company, Schenectady (N.Y.).