Structure of the oxidative dimerization product of 4,6-di(*tert*-butyl)pyrogallol

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The structure of the oxidation product of 4,6-di(*tert*-butyl)pyrogallol, *viz.*, 6,10a-dihydroxy-3,4a,7,9-tetra(*tert*-butyl)-1,2,4a,10a-tetrahydrodibenzo[*b*,*e*][1,4]dioxine-1,2-dione, was established by X-ray diffraction. Dimerization of intermediate 3-hydroxy-4,6-di(*tert*-butyl)-1,2-benzoquinone occurs by the mechanism of Diels—Alder heterocyclization.

Key words: *o*-quinones, X-ray diffraction study, Diels—Alder reaction, heterocyclization, dibenzodioxines.

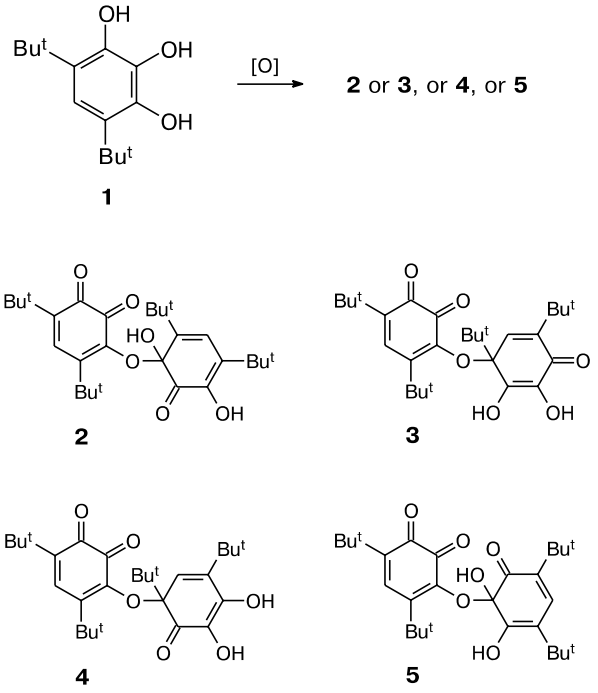
The synthesis and investigation of substituted sterically hindered *o*-quinones have attracted considerable interest because these compounds can be used for the preparation of various heterocyclic systems,[1] the transformation pathway being strongly dependent on the nature of substituents in the starting *o*-quinones. In particular, it was of interest to determine the structure of the oxidative dimerization product of 4,6-di(*tert*-butyl)pyrogallol (**1**). It should be noted that earlier[2] the structure of this dimer has not been unambiguously established, and the choice between possible structures **2—5** (Scheme 1) has not been made.

In the present study, we unambiguously established the structure of the dimer of pyrogallol **1** by X-ray diffraction. There are two independent structurally similar molecules per asymmetric unit (the atomic numbers in the second molecules are increased by 30 compared to those of the first molecule). The molecules superimposed by the O(1), O(2), O(5) and O(31), O(32), O(35) atoms are shown in Fig. 1. The distance between the O(4) and O(34) atoms is 0.404 Å. Hence, in Fig. 2 and in the discussion, we use the data for the first molecule (atoms are represented by displacement ellipsoids drawn at the 30% probability level).

Selected distances and bond angles in molecule *1* of compound **6** are given in Table 1.

The X-ray diffraction study demonstrated that the structure of the dimer is not described by any of structures **2—5** proposed earlier,[2] and this compound has the structure of 6,10a-dihydroxy-3,4a,7,9-tetra(*tert*-butyl)-1,2,4a,10a-tetrahydrodibenzo[*b*,*e*][1,4]dioxine-1,2-dione (**6**) (Scheme 2).

Scheme 1



Apparently, dehydrogenation of starting pyrogallol **1** with *p*-quinone affords the corresponding 3-hydroxy-4,6-di(*tert*-butyl)-1,2-benzoquinone (**7**), which is involved in

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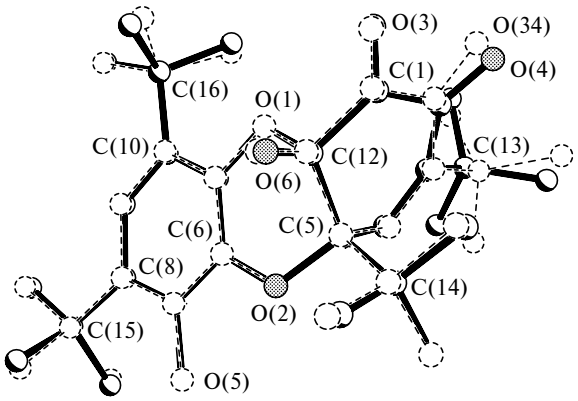
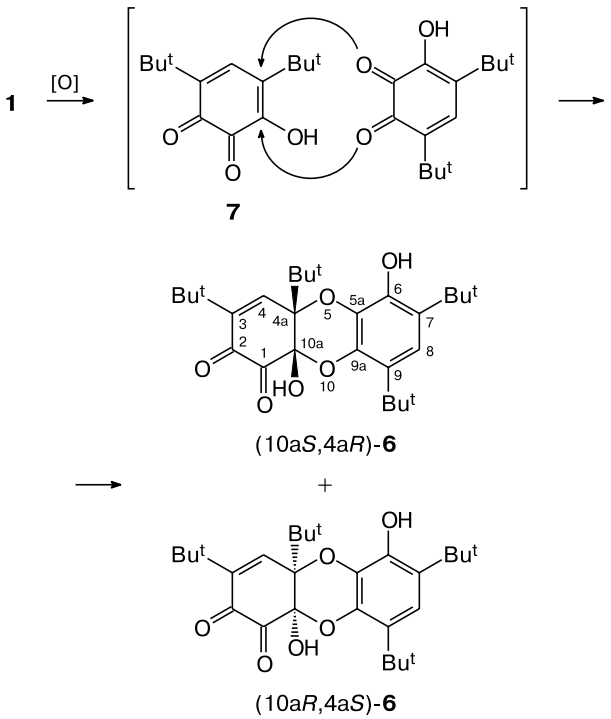


Fig. 1. Two independent molecules of compound **6** superimposed by the O(1), O(2), O(5) and O(31), O(32), O(35) atoms.

Diels—Alder heterocyclization with the second molecule of **7**. Interestingly, the α-diketone fragment of benzoquinone serves as the diene component, and the enol fragment of quinone **7** acts as a dienophile (see Scheme 2). The reaction produces a racemic mixture of two enantiomers, (10a*S*,4a*R*)-**6** and (10a*R*,4a*S*)-**6**.

Although a single crystal of the individual enantiomer of compound **6** was used for the X-ray diffraction study,* the weight of this crystal was insufficient for the investigation by NMR spectroscopy. Because of this, the NMR

Scheme 2



experiments were carried out for solutions of samples containing equal weights of the crystals of both enantiomers.

The ^{1}H NMR spectrum of compound **6** is shown in Fig. 3. The signals for the protons at the double bonds are

* The single crystal used for the X-ray diffraction study was apparently the (10a*S*,4a*R*) enantiomer. The conclusion was drawn using the Cahn—Ingold—Prelog rules.

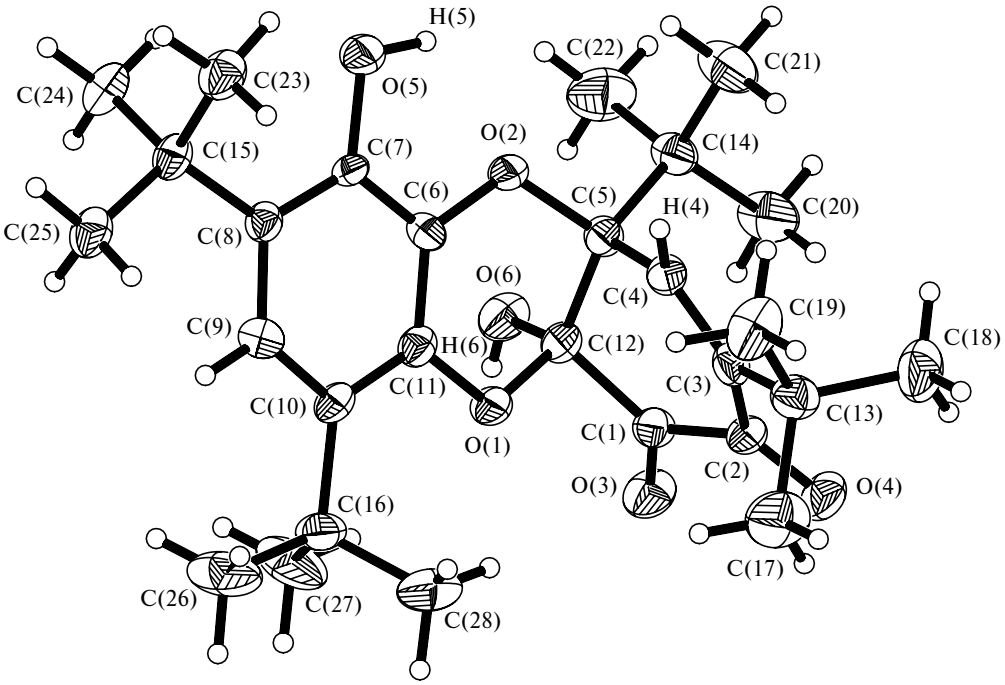


Fig. 2. Molecular structure of 6,10a-dihydroxy-3,4a,7,9-tetra(*tert*-butyl)-1,2,4a,10a-tetrahydrodibenzo[*b*,*e*][1,4]dioxine-1,2-dione (**6**).

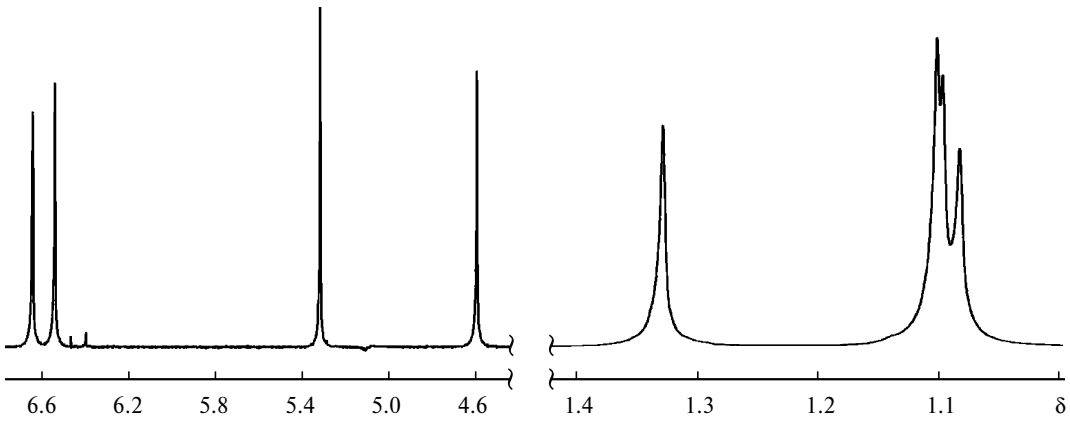


Fig. 3. ^{1}H NMR spectrum of compound **6** in CCl_4.

observed at δ 6.50—6.70; the signals for the protons of the hydroxy groups, at δ 5.32 and 4.59 (was confirmed by deuteration); the signals for the protons of the *tert*-butyl groups, at δ 1.00—1.40. To confirm the presence of both enantiomers in the sample under study, we recorded an NMR spectrum in the presence of the chiral shift reagent, *viz.*, tris[3-(heptafluorohydroxymethylene)-D-camphorato]europium(III). After the addition of the shift reagent, the signal of one of the *tert*-butyl groups in the corresponding region of the ^{1}H NMR spectrum was split into two peaks with virtually equal intensities. This region of the spectrum is shown in Fig. 4. In an analogous experiment with the achiral shift reagent, *viz.*, tris(dipivaloylmethanato)europium(III), we observed only changes in the chemical shifts. Therefore, the ^{1}H NMR spectroscopic studies with the use of the shift reagents provided evidence that the reaction produced a racemic mixture of two enantiomers of **6**.

Table 1. Selected bond lengths (*d*) and bond angles (ω) in molecule *1* of compound **6**

Bond	*d*/Å	Bond	*d*/Å
O(1)—C(11)	1.385(5)	O(2)—C(5)	1.427(5)
O(3)—C(1)	1.205(5)	O(4)—C(2)	1.199(5)
O(5)—C(7)	1.379(5)	O(5)—H(5)	1.13
O(6)—C(12)	1.388(6)	O(6)—H(6)	0.98
C(1)—C(12)	1.516(6)	C(1)—C(2)	1.526(7)
C(2)—C(3)	1.484(6)	C(3)—C(4)	1.329(6)
C(3)—C(13)	1.518(7)	C(4)—C(5)	1.506(7)
C(5)—C(12)	1.538(6)	C(5)—C(14)	1.564(7)
C(6)—C(11)	1.379(6)	C(6)—C(7)	1.378(6)
C(7)—C(8)	1.394(6)	C(8)—C(9)	1.396(6)
C(8)—C(15)	1.533(6)	C(9)—C(10)	1.382(6)
C(10)—C(11)	1.373(6)		
Angle	**ω/deg**	**Angle**	**ω/deg**
C(11)—O(1)—C(12)	117.4(4)	C(6)—O(2)—C(5)	115.5(3)
O(3)—C(1)—C(12)	120.4(4)	O(3)—C(1)—C(2)	121.3(4)
C(12)—C(1)—C(2)	118.2(4)	O(4)—C(2)—C(3)	126.5(5)
O(4)—C(2)—C(1)	116.9(4)	C(3)—C(2)—C(1)	116.6(4)
C(4)—C(3)—C(2)	115.5(5)	C(4)—C(3)—C(13)	126.2(5)
C(2)—C(3)—C(13)	118.1(4)	C(3)—C(4)—C(5)	128.9(4)
O(2)—C(5)—C(4)	109.1(4)	O(2)—C(5)—C(12)	108.2(4)
C(4)—C(5)—C(12)	106.3(4)	O(2)—C(5)—C(14)	105.0(4)
C(4)—C(5)—C(14)	112.5(4)	C(12)—C(5)—C(14)	115.5(4)
C(11)—C(6)—O(2)	122.0(4)	C(11)—C(6)—C(7)	121.4(5)
O(2)—C(6)—C(7)	116.6(4)	C(6)—C(7)—O(5)	117.8(4)
C(6)—C(7)—C(8)	120.5(4)	O(5)—C(7)—C(8)	121.6(4)
C(7)—C(8)—C(9)	115.6(4)	C(7)—C(8)—C(15)	122.7(4)
C(9)—C(8)—C(15)	121.6(4)	C(10)—C(9)—C(8)	125.1(5)
C(11)—C(10)—C(9)	116.8(4)	C(11)—C(10)—C(16)	121.8(4)
C(9)—C(10)—C(16)	121.3(5)	C(10)—C(11)—C(6)	120.6(4)
C(10)—C(11)—O(1)	119.5(4)	C(6)—C(11)—O(1)	119.9(4)
O(6)—C(12)—O(1)	110.4(4)	O(6)—C(12)—C(1)	113.8(4)
O(1)—C(12)—C(1)	98.5(4)	O(6)—C(12)—C(5)	111.5(4)
O(1)—C(12)—C(5)	109.8(4)	C(1)—C(12)—C(5)	112.2(4)

Evidently, the α-dicarbonyl moiety of 1,2-benzoquinones differs from the diene system in the benzoquinone ring.[3] Hence, the addition of typical dienophiles to the 1,2-diketone fragment is less characteristic for these compounds and proceeds in low yield.[4] Two Diels—Alder reactions of 1,2-benzoquinones with furan derivatives[5,6]

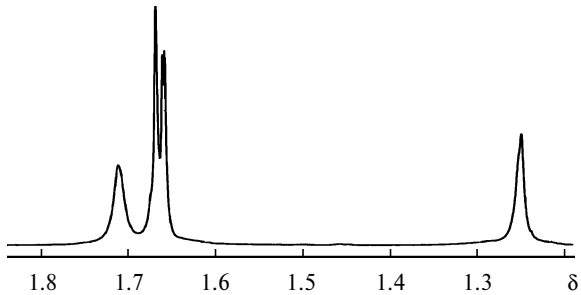
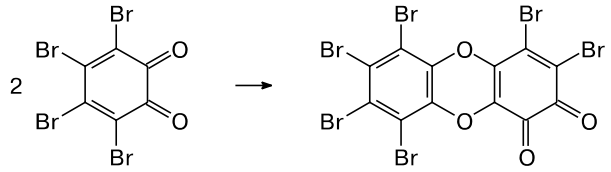


Fig. 4. Upfield region of the ^{1}H NMR spectrum of compound **6** after the addition of the chiral shift reagent (the substrate : reagent molar ratio was 5 : 1).

and thiophene derivatives[7] occurring at the 1,2-diketone fragment were documented. Cyclization of two *o*-bromoanil molecules[8] (Scheme 3) is most similar to the reaction under consideration.

Scheme 3



The compound (10a*S*,4a*R*)-**6** crystallizes in a chiral space group, and both independent molecules are identical enantiomers. The structure of the molecule (10a*S*,4a*R*)-**6** shown in Fig. 2 is characterized by the arrangement of the atoms of the C(6)—C(11) ring and the C(15), C(16), O(1), O(2), O(5), and H(5) atoms in one plane (within 0.034 Å). The H(5) atom is oriented toward the O(2) atom so that the intramolecular H(5)...O(2) contact is 2.35 Å, which is indicative of intramolecular hydrogen bonding. The O(5)—H(5)—O(2) and H(5)—O(2)—C(6) angles are 119.9 and 121.4°, respectively. The O(5)—C(7)—C(8) and O(5)—C(7)—C(6) angles are 121.6 and 117.8°, respectively. Apparently, the inequality of the angles at the C(7) atom is due to the presence of the adjacent *tert*-butyl group at the C(8) atom. This is evidenced by a substantial redistribution of the angles at the C(8) atom (the C(7)—C(8)—C(15) angle is 129.9° and the C(9)—C(8)—C(15) angle is 121.5°). The *tert*-butyl group is rotated about the C(8)—C(15) bond so that the C(7)—C(8)—C(15)—C(25) torsion angle is −175.9°, resulting in a compromise in the intramolecular H...O (between the O(5) atom and the hydrogen atoms at the C(23) and C(24) atoms; 2.31 and 2.48 Å, respectively) and H...H (between the hydrogen atom at the C(9) atom and the hydrogen atoms at the C(25) atom; 2.30 and 2.17 Å) contacts. The second *tert*-butyl group at the C(10) atom is rotated with respect to the plane of the ring so that the C(26) atom is in proximity to the plane of the latter (the C(9)—C(10)—C(16)—C(26) torsion angle is −4.3°). The corresponding contacts between the hydrogen atom at the C(9) atom and the O(1) atom, on the one hand, and the hydrogen atoms of the second *tert*-butyl group, on the other hand, are 2.16, 2.23, 2.28, and 2.40 Å, respectively. The C(5) and C(12) atoms deviate from this plane in the opposite directions by 0.47 and 0.26 Å, respectively, and have a tetrahedral structure.

Two carbonyl groups, C(1)O(3) and C(2)O(4), are located in proximity to each other but are not in one plane. The O(3)—C(1)—C(2)—O(4) torsion angle is 11.5°. The C(12)—C(1)—O(3), C(12)—C(1)—C(2), and C(2)—C(1)—O(3) bond angles are 120.4, 118.2, and 121.3°, respectively; their sum is 359.7°. The distance between the O(3) atom and the H(6) atom in the molecule is 2.49 Å. The sum of the angles at the C(2) atom is 360°. However, the bond angles are different. Thus, the C(1)—C(2)—C(3) and C(1)—C(2)—O(4) angles are 116.6 and 116.9°, respectively, whereas the C(3)—C(2)—O(4) angle is 126.5°. The *tert*-butyl group at the C(8) atom is located so that the C(4)—C(3)—C(13)—C(19) torsion angle is −14.1°; the H...H distances between the hydrogen atom at the C(4) atom and the adjacent hydrogen atoms at the C(19) atom are 2.13 and 2.41 Å; the O...H distances between the O(4) atom and the adjacent hydrogen atoms at the C(17) and C(18) atoms are 2.42 and 2.52 Å, respectively.

The endocyclic angles at the sp^2-hybridized carbon atoms of the six-membered rings bound to the carbon atom of the *tert*-butyl group are smaller (C(2)—C(3)—C(4), 115.5°; C(7)—C(8)—C(9), 115.6°; C(9)—C(10)—C(11), 116.8°).

Experimental

The ^{1}H NMR spectra were recorded on a Varian Unity-300 spectrometer with HMDS as the internal standard. The IR spectra were measured on an IR-75 instrument in Nujol mulls. The CD spectra were recorded on an Olis DSM 17 CD spectropolarimeter (l = 2 mm).

6,10a-Dihydroxy-3,4a,7,9-tetra(*tert*-butyl)-1,2,4a,10a-tetrahydrodibenzo[*b*,*e*][1,4]dioxine-1,2-dione (6) was synthesized according to a known procedure.[2] Recrystallization from hexane afforded yellow crystals, m.p. 153—154 °C. The elemental analysis data, the ^{1}H NMR spectrum, and the melting point were completely identical to the published data.[2]

X-ray diffraction study. Single crystals of quinone (10a*S*,4a*R*)-**6** were grown by slow evaporation from a 1 : 1 petroleum ether—chloroform mixture. The melting point of the individual enantiomer (10a*S*,4a*R*)-**6** differs from that of racemate **6** and is 145—146 °C. The unit cell parameters of the crystal of **6** and the three-dimensional set of reflection intensities were measured on a KUMA-DIFFRACTION KM-4 diffractometer (Mo-Kα radiation, graphite monochromator) from a single crystal of dimensions 0.02×0.45×0.61 mm. The compound ($C_{28}H_{40}O_6$) crystallized in the orthorhombic system, a = 14.202(3) Å, b = 16.999(3) Å, c = 22.889(5) Å, V = 5525.9(19) Å^3, M = 472.60, space group $P2_12_12_1$, Z = 8, d_{calc} = 1.136 g cm^3. No absorption correction was applied, μ(Mo-Kα) = 0.078 mm^{-1}. The intensities of 5073 reflections were measured within an independent region of reciprocal space (2θ ≤ 50.10°) with the use of the ω/2θ-scanning technique. After rejection of the systematic absences, the X-ray data set contained 5044 reflections with $I > 2\sigma(I)$. The structure was solved by direct methods and refined by the full-matrix least-squares method with anisotropic displacement parameters for nonhydrogen atoms against F^2 using the SHELXL-97 program package.[9] The H atoms were located in difference electron density maps and refined using a riding model[9] (except for the H atoms of the hydroxy groups, which were not refined). The final R factor

was 4.2%; 614 parameters were refined, GOF was 0.856. The final electron difference map contained the maximum and minimum electron densities of 0.212 and –0.223 e $Å^{-3}$, respectively.

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